Drought Monitoring and Impact Assessment in the Mekong River Basin

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Client

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1.1 The Mekong River Commission

The Mekong River Commission (MRC) is an international river basin organisation built on a foundation of nearly 50 years of knowledge and experience in the region. On the 5th of April 1995, Cambodia, Lao PDR, Thailand and Viet Nam, signed the "Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin". This agreement formed the Mekong River Commission (MRC), which replaced the Committee for Coordination of Investigation of the Lower Mekong Basin (the Mekong Committee) and the Interim Mekong Committee, which were established in 1957 and 1978 respectively.

The MRC provides the institutional framework to promote regional cooperation in order to implement the 1995 Agreement. It serves its Member States by supporting decisions and promoting action on sustainable development, protection of ecological balance and poverty alleviation, as a contribution to the UN Millennium Development Goals.

The mission of the MRC is to promote and coordinate sustainable management and development of water and related resources for the countries' mutual benefit and their people's well-being. To this end, the work of the MRC supports the Mekong Programme, a regional cooperation programme for the sustainable development of water and related resources in the Mekong River Basin.

Figure 1: Map of Mekong and MRC countries.

1.2 Drought in the Mekong Basin

It is widely accepted that drought is a serious threat to the people and environment in the Mekong River Basin. There are however some misconceptions that hampered the implementation of an effective drought initiative. The main justifications why an effective Drought Management Initiative is highly required will be discussed briefly here and includes:

1. Impact of drought is of the same magnitude or even higher compared to the impact of floods
2. Procedures set in place for flood management cannot be transferred directly for drought management.
3. Drought assessment and alleviation is far more complex than flooding.
4. Climate change will increase drought substantially.
5. Floods provide many positive services; drought not.
6. Drought is a trans-boundary and basin-wide issue.

These six issues will be clarified in the next sections to justify why an effective and operational drought program is essential for the Mekong River Basin.

1.2.1 Impact of flood vs. drought

It is clear that floods have devastating impact on people living in the Mekong River Basin. Almost every year millions of people are affected by the negative impacts of floods. However, the number of people affected by drought is probably much higher (Figure 2). In contrast to floods, the number of people affected by drought is very difficult to assess. Drought is a *slow killer* and effects are occurring gradually, while for flooding the impact is instantaneous. Results can be monitored easily in terms of for example number of people being displaced. Typical examples of impact of drought and floods for the four LMB countries are presented in Table 1 to Table 4.
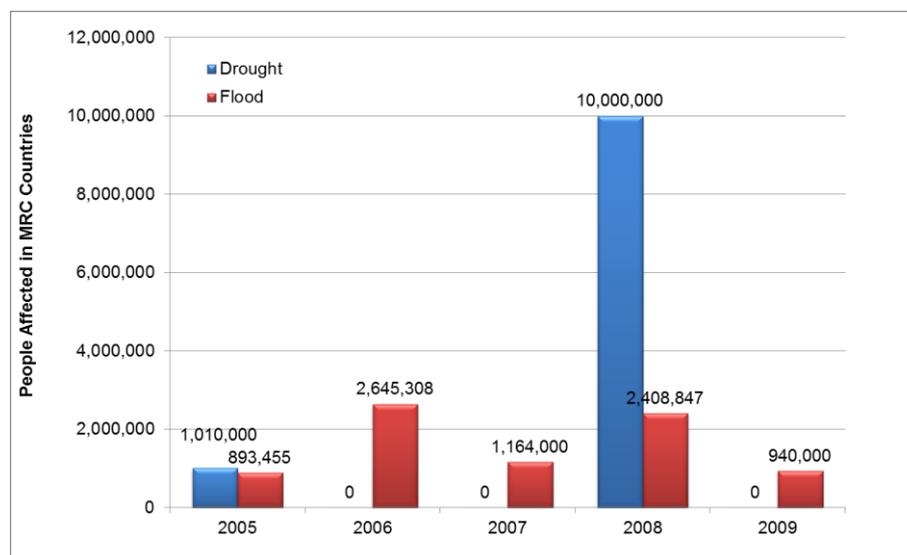

Figure 2: Number of people affected by drought and floods in the LMB countries (source International Disaster Database).

Table 1: Typical examples of impact of drought and floods in Cambodia.

Disaster	Date	Affected (person)	Damage (1000s US$)	Source
Flood	Jun-1996	1,470,000	100	IDD
Flood	Jul-2000	1,300,000	1,500	IDD
Flood	Aug-2001	3,448,053	160,000	IDD
Flood	Aug 2002	1,669,182	15,000	IDD
Drought	2003-2005	2,000,000	Unknown	ADB
Drought	Jun-2004	5,000,000	100,000	IDD

IDD=International Disaster Database
ADB=Asian Development Bank

Table 2: Typical examples of impact of drought and floods in Lao PDR.

Disaster	No Events	Affected (person)	Source
Drought	5	4,250,000	WFP
Flood	16	3,244,150	WFP

WFP = World Food Programme

Table 3: Typical examples of impact of drought and floods in Thailand.

Disaster	Date	Affected	Impact	Source
Drought	2003-2005	650,000 ha	Increased farm production cost 40%	ADB
Drought	2009	2,444,010 ppl	Decreased agricultural product	GAR
Flood	2009	819,822 ppl	Unknown	GAR
Drought	2010	Unknown	Lost 75% of Cassava production & increased price 60%	Bangkok Post

ADB = Asian Development Bank
GAR = Global Assessment Report

Table 4: Typical examples of impact of drought and floods in Vietnam.

Disaster	Date	Affected	Impact	Source
Drought	2003-2005	10,000 ha	$ 60 million (Cuu long delta)	ADB
Drought (North central)	June 2010	40,000 hhds, 250,000 ha	Not enough clean water; crops dried up; high tem.	VietNamNet

ADB = Asian Development Bank

1.2.2   Flood management procedures are different for drought management.

Procedures set in place for flood management cannot be transferred directly for drought management. The entire management of drought requires a completely different approach compared to floods. Floods and drought have a completely different dimension regarding forecasts, impacts and mitigation (Figure 3).

Probably the most striking difference in terms of disaster management focus is on the domain area: rivers for flood versus land for drought. While flood mitigation can focus on river management only, drought management should include surface water, soil water and groundwater simultaneously. In the growing international literature on floods and drought this is often referred to as "blue" and "green" water. Blue water refers to the "visible" water, e.g. water in streams, rivers and reservoirs. Green water refers to water falling as precipitation, stored in

the soil and subsequently evaporated by vegetation. On a global scale this green water use is of several magnitudes bigger than the blue water use (Figure 4).
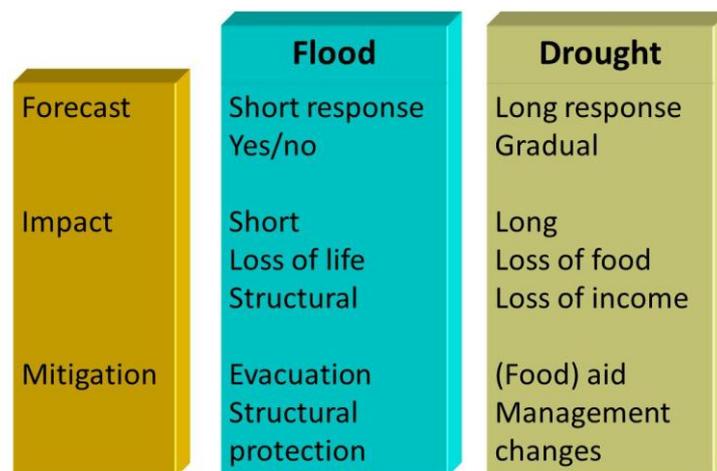
Figure 3: Flood and Drought pillars (source: Droogers and Immerzeel).
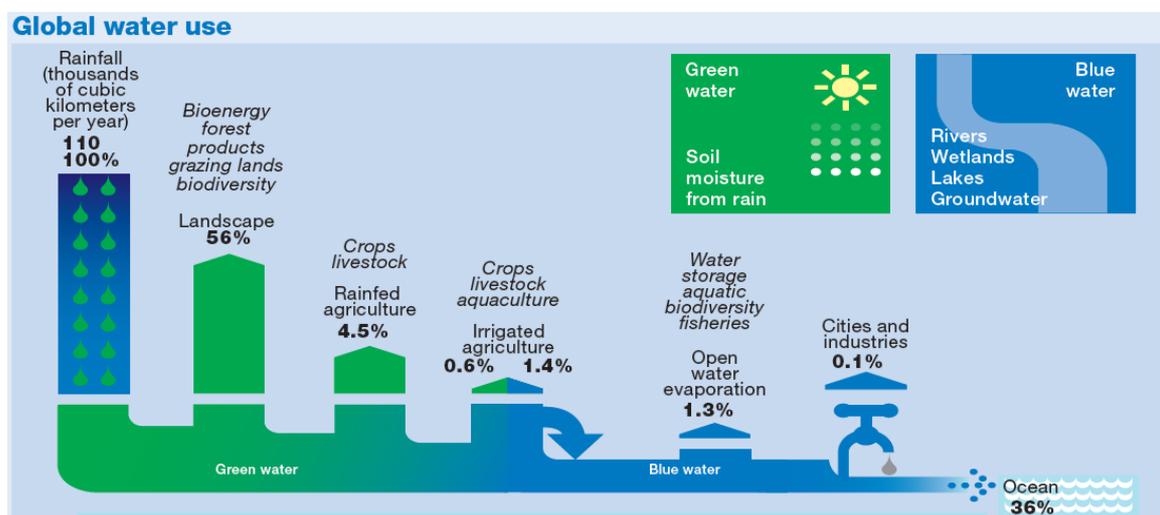
Figure 4: "Green" and "Blue" water on a global scale (source: Comprehensive Assessment of Water and Agriculture).

1.2.3   Drought assessment and alleviation is far more complex than flooding

The impact of drought has a local character within a basin context. Drought events develop over large areas, but have a high spatial differentiation (Figure 5, left). The impact of drought shows an even more spatial distribution (Figure 5, right) as a result of a complex interaction between different processes. Floods, in contrast, occur in well distributed areas around the river. Moreover, drought events are far more difficult to define as they manifest in gradients from mild to severe, why floods occur in a so-called a binary mode: flooded or not flooded.

Figure 5: Precipitation anomaly based on TRMM satellite (left) and Vegetation anomaly based on MODIS satellite (right) for the 2009-2010 season.

1.2.4   Climate change will increase drought substantially

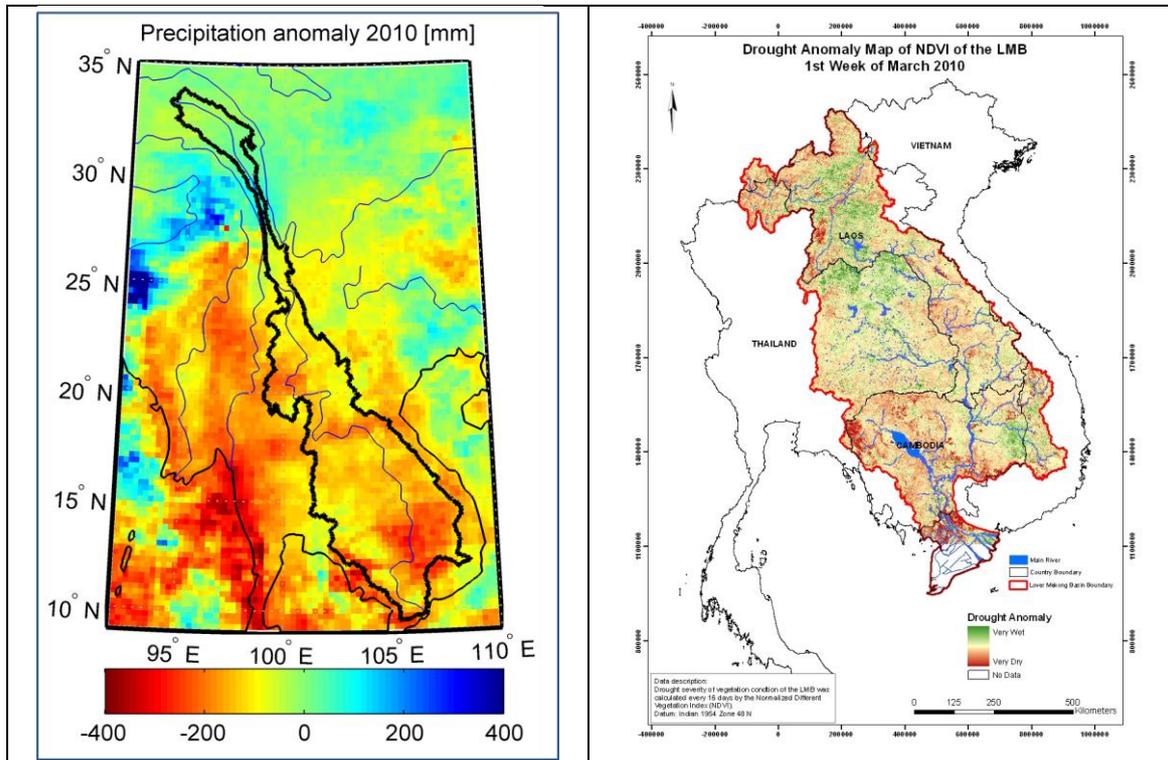The Intergovernmental Panel on Climate Change (IPCC) concluded in their latest Assessment Report that low rainfall and higher temperatures will intensify drought in the Mekong Region substantially (Figure 6). A first assessment of the impact of climate change on drought was undertaken using one Global Circulation Model (GCM) and the SWAT simulation model. One of the main conclusions resulting from the study was that "Many scientists are now concluding that these (climate) predictions are gross underestimates and that the region will likely experience the upper extremes of the climate scenarios forecast in the last IPCC assessment". Other key observations are that:

- Average daily temperatures across Southeast Asia have increased 0.5 to 1.5ºC between 1951 and 2000 (IPCC 2007). Thailand's temperatures have reportedly increased 1.0 to 1.8ºC in the past 50 years; average daytime temperatures in the month of April have been particularly high at 40ºC (ADB, 2009). Viet Nam's temperatures increased by 0.7°C during this same period (ADB 2009). Daily maximum and minimum temperatures are also increasing.
- Annual maximum flows at Kratie are indicted to increase both in terms of their mean and inter-annual range.
- A major impact of global warming rests with the increase in the level and variance of flows during the dry season from year to year.
- This analysis emphasises that there is the prospect of a far more wide ranging modification of the Mekong flow regime than simply a change to mean discharge or the incidence and severity of floods and drought. In general terms any increase in the year to year variability in the statistics points towards a far less certain hydrological environment, which has wide ranging implications for food security and the environment

as well as for the economic returns from water resources investments, such as hydropower schemes.

Climate change and the changes in flow regimes can be observed already. Figure 8 indicates that low flows are more frequent over the last decade. The figure shows the joint distribution of the annual maximum flood discharge ($m^3 s^{-1}$) and the volume of the annual flood hydrograph (km^3) at on the Mekong at Kratie (1924 – 2006). The 'boxes' indicate one (1δ) and two (2δ) standard deviations for each variable above and below their respective means. Events outside of the 1δ box might be defined as 'significant' flood / drought years and those outside of the 2δ box as historically 'extreme' flood / drought years.

An important aspect of using climate change scenarios is to downscale these scenarios to a level appropriate to undertake smaller scale assessments. In principle two methodologies exists to undertake this down-scaling: (i) using a regional climate model, (ii) statistical downscaling.

Within the MRCS initial studies have been undertaken using the regional climate model PRECIS. The PRECIS (Providing Regional Climates for Impacts Studies) model is one of the most frequently used regional climate models (RCM) in Southeast Asia over the last five years. One of the major drawbacks of the use of RCMs is that, given the complexity and the time-consuming calculations, only a limited number of GCMs can be used to define the boundary conditions. At the same time are these boundary conditions by enlarge responsible for the final result of the overall trends.

The statistical downscaling approach has the advantage that it can be performed relatively quickly so that many GCMs can be used in the assessment. The ADAPT project undertaken by MRCS in association with a large group of international research organisations is a typical example of such an approach.

Obviously a combination of these two provides the most relevant results to be used to make strategic decisions regarding drought management and preparedness.
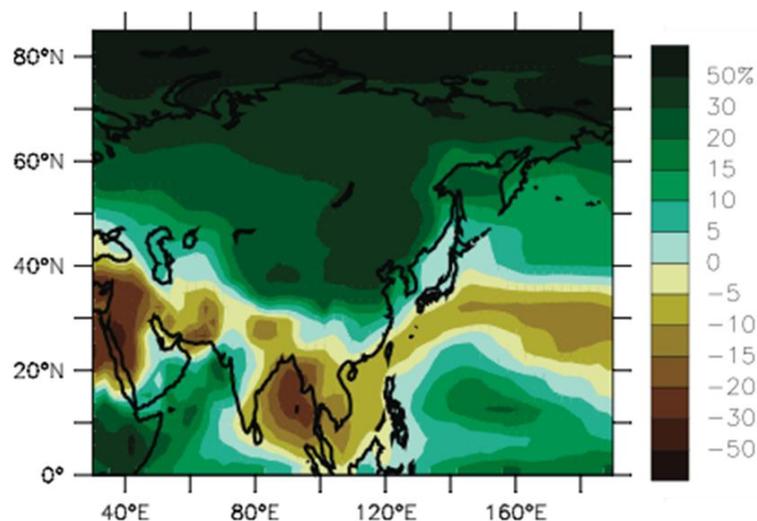

Figure 6: Precipitation changes (Dec-Jan-Feb) from the MMD-A1B simulations. Dec-Jan-Feb mean change between 1980 to 1999 and 2080 to 2099, averaged over 21 models (source: IPCC).
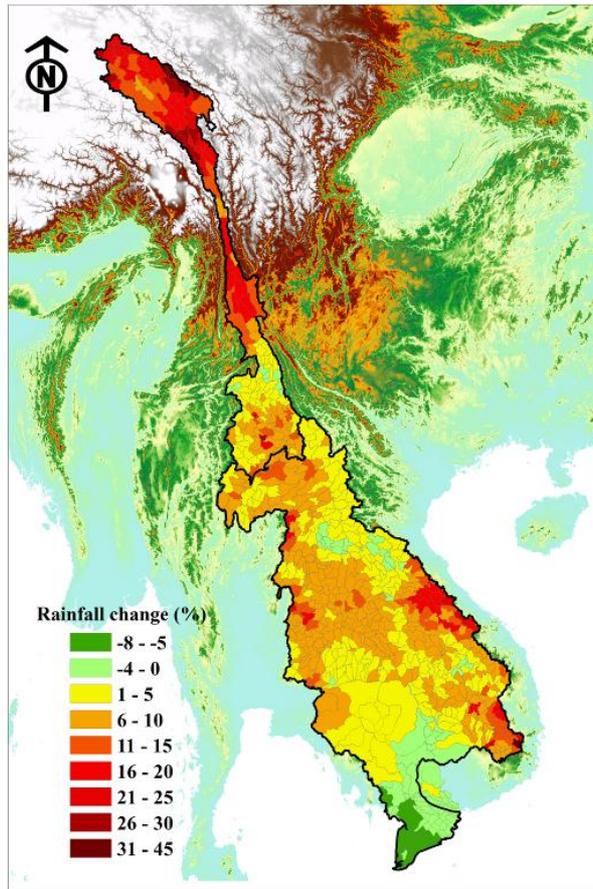
Figure 7: Downscaled climate change precipitation scenario. Indicated is the change (%) of mean annual rainfall during 2010-50 relative to 1985-2000 for the ECHAM4-A2 GCM (source: Kittipong Jirayoot, 2009).
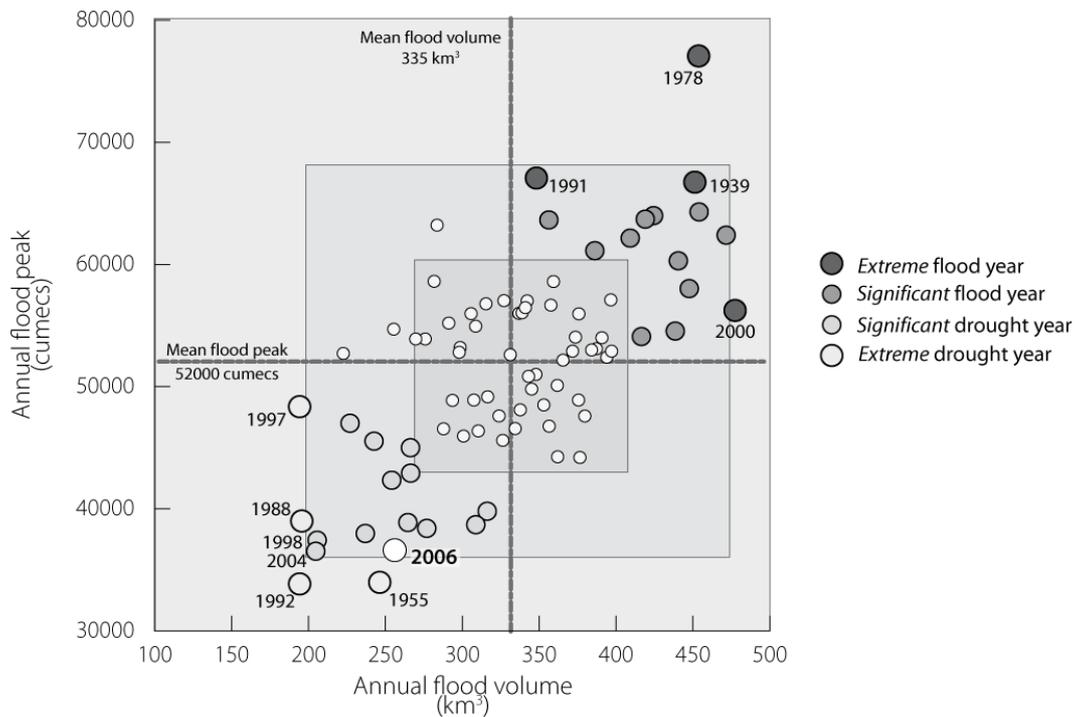
Figure 8: Scatterplots of the joint distribution of the annual maximum flood discharge (cumecs) and the volume of the annual flood hydrograph (km3) at on the Mekong at Kratie (1924 – 2006) (source: Adamson and Bird, 2010).

1.2.5   In contrast to drought floods provide positive services

It is widely accepted that drought events have only negative impacts, while floods provide, besides negative impacts, also specific services. The latter is especially true for the Mekong Basin. Typical examples of services floods provide are the more adequate moisture conditions to plant a crop after the flooding. This type of positive services is often referred to as recession irrigation. A rising river overtops its banks and inundates the plains alongside the river. Crops benefit from the receding flow by enhanced residual moisture conditions.

For the Mekong Basin the most relevant positive impact of flooding and high flows is the well-known Tonle Sap / Great Lake system. It is the most important inland wetland in Southeast Asia and it supports a huge population through its enormous fisheries productivity and water supply; and provides the last refuge for some of Asia's most globally significant biodiversity. Drought in contrast has no positive components and it can only be considered as a threat to humans, livestock, wildlife and the entire environment.

Figure 9: Tonle Sap flow directions (source: http://www.tsbr-ed.org).

1.2.6 Drought is a basin-wide issue

An important consideration for the proposed Drought Management Initiative is the basin-wide and trans-boundary dimension of drought. Without such a trans-boundary dimension drought should probably not being adopted by the MRC. However, there are many trans-boundary dimensions associated with drought in the Mekong Basin. The most relevant are:

- Low flows are a result of reduced recharge and/or increased withdrawals in upstream parts of the Mekong River.
- Flow regulation by reservoirs can overcome dry spells and is clearly a trans-boundary issue. At the same time can reservoirs being used to tap water, reducing total annul flows to downstream areas.
- Market prices are highly affected by drought. So drought in one region will reduce harvests in that region, inducing higher prices affecting all farmers in the region positively.
- Drought is a result of lower rainfall and is not restricted by country boundaries. Rainfall forecasting and early warning systems for drought should therefore be taken at basin level.

So far, drought has been considered as country specific problems. This has for example leaded to different definitions and drought risk assessments. For example, the four member states have created drought assessment maps under various assumptions and names:

- Cambodia: Drought risk area
- Lao PDR: Percentage of households affected by drought
- Vietnam: Drought hazard zone
- Thailand: Drought hazard zone

Maps associated to these assessments can be seen in Figure 10. It is clear that these maps are all using different definitions and an attempt to combine these maps to one generalized map for the entire LMB fails because of these different methodologies and definitions.
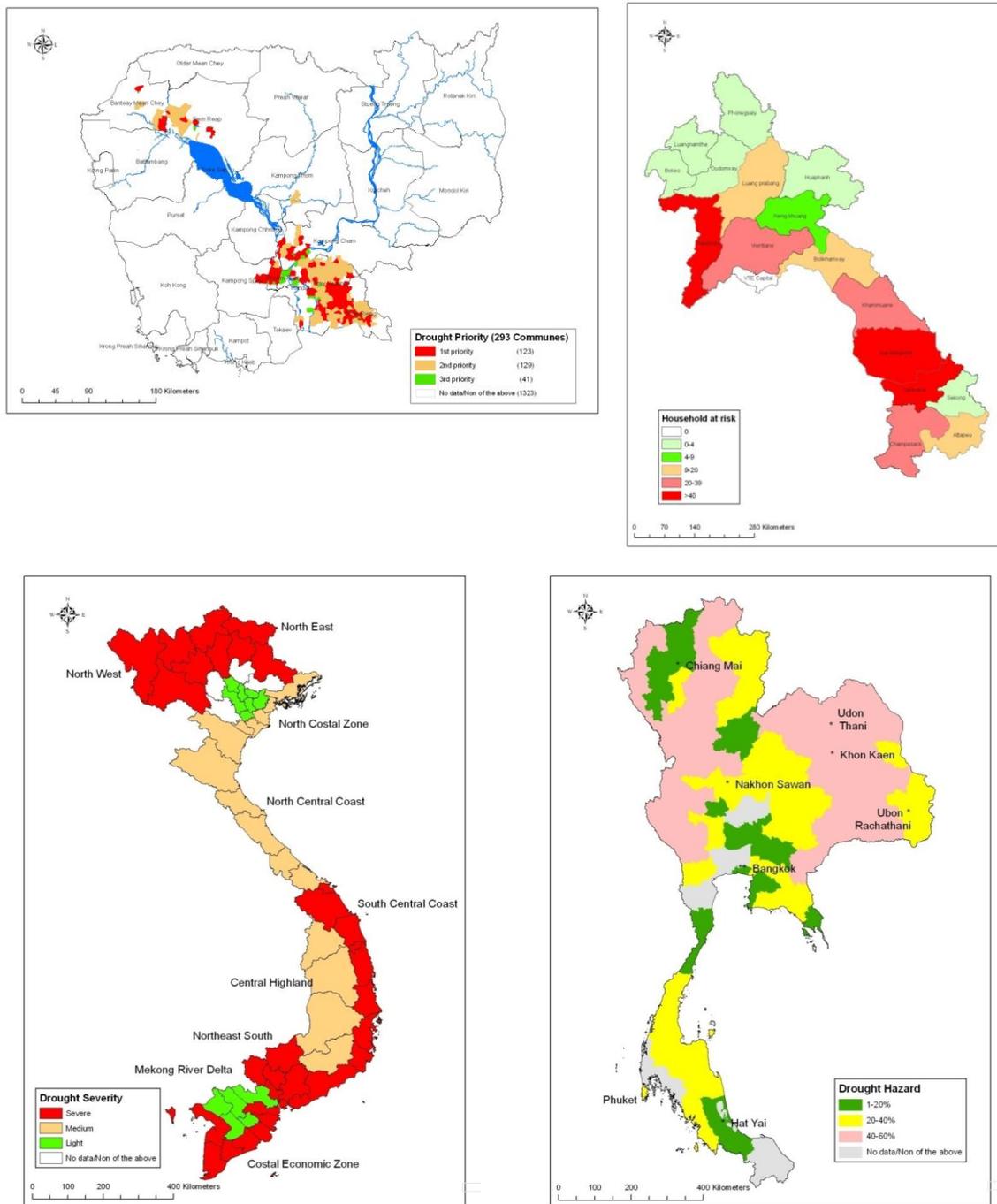
Figure 10: Drought risk maps of the four MRC member states.

The notion of drought as a meteorological hazard in tropical monsoon regions is not perhaps one that fits naturally with conventional perceptions. The term "Monsoon" is virtually synonymous with torrential rainfall, moisture surplus, floods and climatic predictability. Drought on the other hand is more generally associated with the marginal rainfall climates of arid and semi-arid regions, which show high variability and low reliability from year to year, such that rainfall deficits are common and often severe.

Drought is by many considered to be the least understood of all major hazards (Keyantash and Dracup, 2004). Impacts are "non-structural", unlike other hydro-meteorological extremes such as floods and typhoons, and they are much more widespread geographically. The severity of a

drought and its impact is dependent not only on its duration, intensity and spatial extent, but also on the specific environment and the economic activities carried out within it as well as the capacity of the prevailing institutional and social systems to cope with it.

In the Mekong Basin and along the mainstream there are a range of environments and water demands that respond differently to the various and complex elements of a drought event. The most important characteristics of drought in the Mekong basin are:

- Below normal flows during the flood season affect the timing, depth and duration of wetland inundation and the inflows to the Great Lake / Tonle Sap system with negative consequences upon fisheries and therefore upon the economy of Cambodia.
- Deficient flows during the dry season months permit more extensive saline intrusion in the Viet Nam delta which reduces water availability for irrigation. This leads to lower yields, reduced planted area and significant economic loss for one of the world's largest producers of rice for the global market. Low water levels also restrict navigability and reduce river-borne trade.
- Rainfall shortfalls and unexpected precipitation patterns in both the wet and dry seasons can result in agricultural losses, which can become so large that they lead to reductions in regional and national economic growth targets, as has happened in north east Thailand in 2004.

The definitive feature of the drought process is the accumulation of a moisture deficit, which may be measured in terms of rainfall, stream flow or soil moisture. The severity of an event, however, is not only a function of the levels that this deficit reaches, but also the timing of crucial moisture shortfalls. For example, if these are reached during the grain filling stage of crop development, then the severity of the event from an agricultural point of view is maximized.

In this report a framework is presented for drought monitoring and impact assessment that should be further developed and implemented as part of a Drought Management Initiative (DMI) for MRC. A number of technical examples of drought indicators, hazard indicators, and vulnerability indicators are already given in this report that can be included in the final DMI.

2.1   Definitions

The drought phenomenon is often grouped into four types (Wilhite and Glantz, 1985):

- **Meteorological** or climatological drought, which focuses on the degree of "dryness" in terms of an accumulated rainfall deficit.
- **Agricultural** drought, which expresses the precipitation shortfall primarily in terms of its impact upon crop production through insufficient soil moisture. It generally applies to rainfed agriculture, though irrigated crops can be affected when the water resources themselves become restricted or too expensive.
- **Hydrological** drought refers to shortages in both surface and ground water. This can take the form of critically low river flow, drawn down reservoir storage and deeper groundwater levels which make pumped abstraction too expensive or mechanically impossible.
- **Socio-economic** definitions of drought associate the supply and demand consequences for economic goods. For example, if the water shortage becomes so severe that the cooling water supply to key thermal power stations is reduced, the event would be severe. Similarly, energy outputs from hydropower schemes can be curtailed due to low stream flow and low levels of reservoir storage. There are industrial, agricultural, environmental and social consequences from any curtailment of water supply and water use during droughts.

Meteorological drought is the prime mover in the sequence. The first consequence of an accumulated rainfall deficit is a reduction in soil moisture storage, which once it reaches a critical level, will have impacts upon crops and animal grazing. Agricultural impacts are therefore the first to appear and in most cases provide the first confirmation that there is in fact a drought of any sort at all. These impacts can vary from crop to crop, farm to farm, region to region and depend upon the crop and its resistance to moisture stress, the stage in its growth, whether there are alternative water supplies other than rainfall and whether livestock can be provided with alternative grazing.

As the rainfall and moisture deficit continues to accumulate, hydrological drought begins to manifest itself. Firstly, natural streamflows decrease and fall below normal, ultimately causing a water resources shortfall as reservoirs and other sources of water supply become drawn down. If the event has a long duration and particularly in the case of multi-year droughts, groundwater levels fall and abstraction can become too expensive, too damaging or even mechanically impossible.

Finally, drought becomes apparent as a socio-economic process of water shortages and their impacts. There may be food price increases due to reduced domestic agricultural output and (possibly) their replacement with more expensive imports. There may be power rationing due to reduced generating capacity and some industries that are high consumers of water (petrochemicals, metallurgical, bottling plants) might have to reduce production, with secondary consequences for employment, prices, the availability of goods and national economic growth. This sequential process in the development of and linkages between the various components of the overall concept of drought is presented schematically in Figure 11. Also shown are some of the environmental impacts which start to become apparent from the start. For example, many

plants leaf and flower on the arrival of the first seasonal rainstorms. If these are delayed or do not happen to the necessary degree, there are consequences for insect and birdlife, for natural grazing and, not insignificantly, the risk of fire.
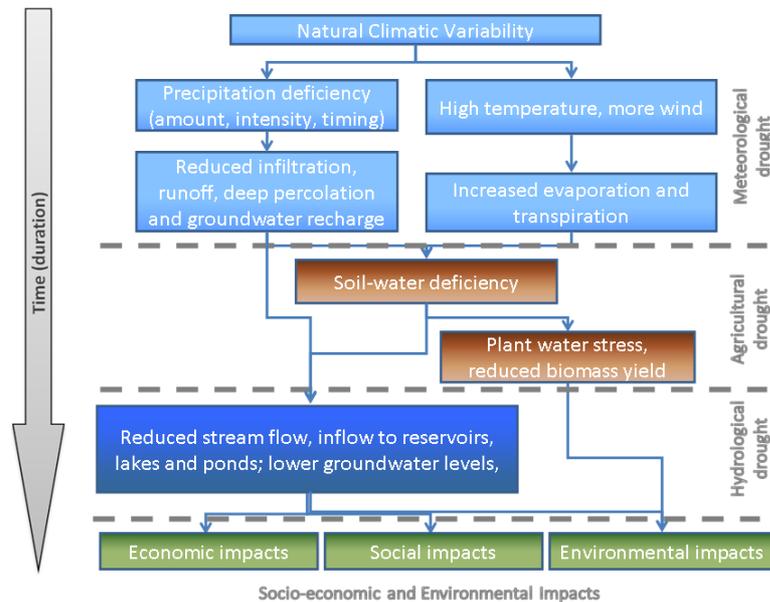

Figure 11: Drought Monitoring and Impact Assessment Toolbox (DMIAT).

It is proposed to follow the above described framework for assessing drought in the LMB. For each type of drought a number of commonly used indicators will be discussed hereafter. Drought indices assimilate thousands of bits of data on rainfall, agriculture, hydrology and other water related indicators into a comprehensible big picture. A drought index value is typically a single number, far more useful than raw data for decision making.

2.2   Meteorological Drought

There are several meteorological indicators for monitoring drought that vary in complexity and applicability. Most indicators describe how much precipitation for a given period of time has deviated from historical averages and will be explained here.

2.2.1   Rainfall anomalies

A rainfall anomaly is expressed as the percentage of normal precipitation it is one of the simplest measurements of rainfall for a location. Analyses using the percentage of normal are very effective when used for a single region or a single season. Percentage of normal is also easily misunderstood and gives different indications of conditions, depending on the location and season. It is calculated by dividing actual precipitation by normal precipitation. This can be determined for a variety of time scales. Usually these time scales range from a single month to a group of months representing a particular season, to an annual or water year.

One of the disadvantages of using the percentage of normal precipitation is that the mean, or average, precipitation is often not the same as the median precipitation. The reason for this is

that precipitation on monthly or seasonal scales does not have a normal distribution. Use of the percentage of normal comparison implies a normal distribution where the mean and median are considered being the same. This makes it difficult to link a value of a departure with a specific impact occurring as a result of the departure, inhibiting attempts to mitigate the risks of drought based on the departures from normal and form a plan of response (Willeke et al., 1994).

2.2.2 Standardized Precipitation Index

The Standardized Precipitation Index (SPI) is an index based on the probability of precipitation for any time scale. A deficit of precipitation has different impacts on groundwater, reservoir storage, soil moisture, snowpack, and streamflow and this was the base to the development of the Standardized Precipitation Index (SPI) in 1993. The SPI was designed to quantify the precipitation deficit for multiple time scales. These time scales reflect the impact of drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee et al. (1993) originally calculated the SPI for 3–, 6–, 12–, 24–, and 48–month time scales.

The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI.

McKee et al. (1993) used a classification system to define drought intensities resulting from the SPI. McKee et al. (1993) also defined the criteria for a drought event for any of the time scales. A drought event occurs any time the SPI is continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and intensity for each month that the event continues. The positive sum of the SPI for all the months within a drought event can be termed the drought's "magnitude".

2.2.3 Moisture Availability Index

The Moisture Availability Index (MAI) (Hargreaves and Keller, 2005) has been used in numerous studies at the country and global level to evaluate the climate resource for agricultural production. The MAI is the ratio between monthly precipitation and reference evapotranspiration and this takes into account water requirements too. The MAI can be calculated at different time scales (monthly, seasonal, and annual).

2.3 Agricultural Drought

There are several agricultural drought indices available that either describes the soil moisture condition, vegetation status or actual crop transpiration.

2.3.1 Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is a simple numerical indicator that can be used to analyse remote sensing measurements, typically but not necessarily from a space platform, and assess whether the target being observed contains live green vegetation or not. In data-scarce environments time series analysis of the Normalized Difference Vegetation Index (NDVI) can provide valuable information in assessing spatial distributed linkages between climate properties, vegetative phenological cycles and rain-fed land use (Tucker, 1979).

The NDVI assumes that the difference between the near-infrared (NIR) and red (RED) reflectance divided by the sum of both (Equation 1) is a quantitative measure of photosynthetic activity (Prince 1991). Analysis of remotely sensed NDVI imagery has successfully been applied in a variety of fields such as drought assessment (Immerzeel et al., 2004).

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

Equation 1: Calculation of the NDVI.

With:
NDVI	=	*Normalized Difference Vegetation Index;*
NIR	=	*Near InfraRed reflectance;*
RED	=	*Red reflectance;*

2.3.2 Soil moisture deficits

The soil moisture deficit can be considered as an integrated factor determined by a range of processes such as precipitation, evapotranspiration, runoff, and groundwater recharge. Since soil moisture is a dominant factor for vegetation growth, soil moisture deficit can be seen as an overall drought index. Soil moisture determination was always hampered with difficult and very local specific measurements using tensiometers, neutron sondes, capacitive sensors and/or TDR. However satellite information using passive or active microwave has moved the observation of soil moisture deficit to a higher level. One of the standard sensors being used nowadays is the AMSR-E on board of the Aqua satellite. Various derived products exist and can be obtained from the Goddard Earth Science Data and Information Services Center (GES DISC).

2.4 Hydrological Drought

Hydrological drought is probably one of the easiest and most commonly one used. Focus on the so-called "blue" component of water, in contrast to "green" water, has always dominated the hydrology and water resources analysis. For hydrological drought assessments many varieties exist, but they are all based on comparing "regular" flows with time-specific flows. Comparisons are often done at weekly, 10-days, monthly, seasonal or annual time-scales. Daily flow rates are not commonly used, and are more the domain of flood analysis.
Reservoir levels are a second component of the hydrological drought analysis. With the advent of satellites innovative methods are becoming available to monitor real-time reservoir levels of any reservoir in the world even without having access to the site. An interesting example of this is the ENVISAT sensor as developed and maintained by European Space Agency (ESA). In the next chapter this will be demonstrated for the Tonle Sap.

3 Drought Monitoring in the Mekong basin

This Chapter will demonstrate some of the methods for drought monitoring as introduced in the previous Chapter. The objective is not to deliver a full drought analysis of the Mekong River Basin, but should be considered as a first introduction and demonstration of options that might be included in an operational drought monitoring initiative at MRC.

3.1   Meteorological Drought

3.1.1   Precipitation anomalies

To evaluate the anomalies of precipitation, TRMM (Tropical Rainfall Measuring Mission) daily precipitation data have been downloaded from NASA[1]. This is a joint U.S.-Japan satellite mission to monitor tropical and sub-tropical precipitation and to estimate its associate latent heating. The dataset has a spatial resolution of 0.25 x 0.25 degrees.

For the purpose of this study we have calculated the precipitation anomalies for September 2009 through May 2010, with respect to the average of September 2000 through May 2010. The anomalies are calculated for each month separately, and for the entire period as a whole. Figure 12 shows the precipitation anomalies for the entire period September 2009 through May 2010. The left plot represents the anomalies in mm, while the right plot shows the anomalies in percentages.
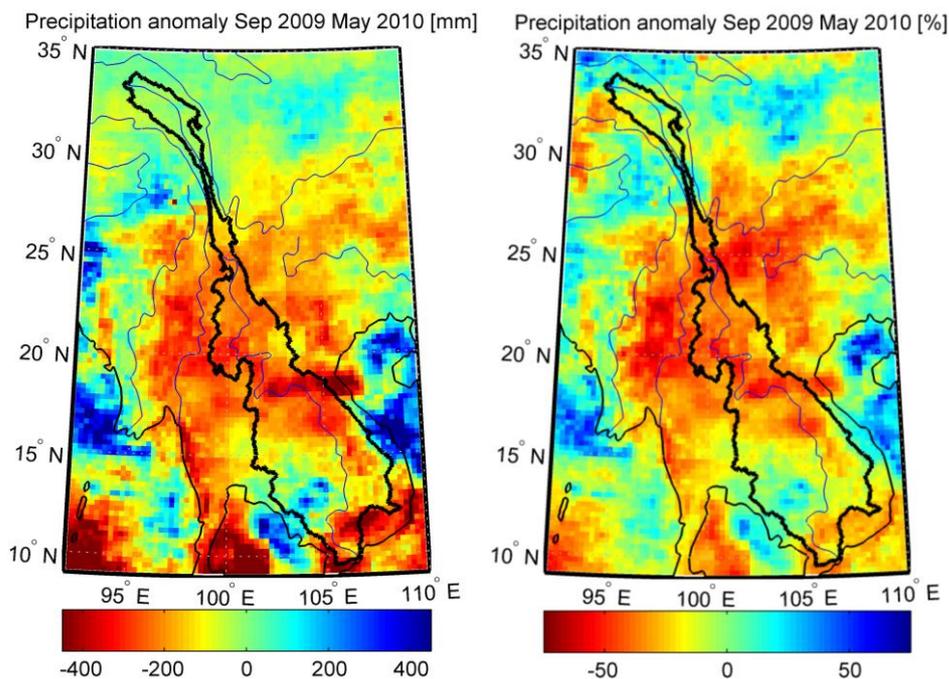

Figure 12: Precipitation anomaly in mm (left) and in percentages (right) of Sep 2009 through May 2010 with respect to the same months averaged over 2000-2010.

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[1] http://mirador.gsfc.nasa.gov/collections/TRMM_3B42_daily__006.shtml

It is noticed that the precipitation amount for September 2009 through May 2010 is below average. Especially the middle and south-eastern part of the basin show very low amounts of precipitation. These differences vary between more or less -200 and -400 mm on average in these regions. Despite these low precipitation anomalies in these regions, the anomalies in the northern and south-western part are not small. Especially the rainfall in the south-western part is above average.

The figures with the anomalies per month are shown in Appendix 1. January 2010 seems to behave like average conditions, except for the wet conditions in the middle and south-eastern part of the basin. May 2010, however, shows very low precipitation anomalies. Some areas receive less than 100 mm precipitation during this month, when compared to the average situation.

3.1.2   Standardized Precipitation Index

As mentioned in Section 2.2.2, the Standardized Precipitation Index (SPI) was designed to quantify the precipitation deficits for multiple time-scales. According to McKee et al. (1993) the SPI can be calculated for 3, 6, 12, 24, or 48 months, which represent typical time-scales for precipitation deficits. A disadvantage of the use of the SPI is the need of long time-series (Hayes, 1999). Guttman (1999) recommends using at least 50 years of data for drought periods of 1 year or less, and more for multi-year droughts. Other studies, however, by Hayes (2006) and Naresh Kumar et al. (2009) used shorter periods of 39-, and 30-years, respectively. For the calculation of the SPI in this study we have used the same TRMM data as used in the previous section. Unfortunately we only have a time-series of 11 years available for the calculation of the SPI.
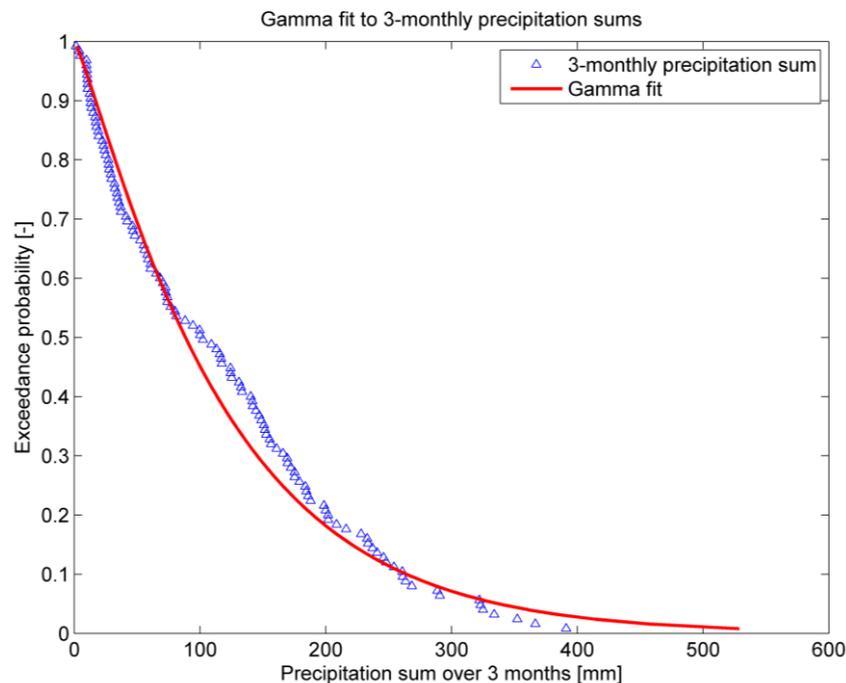

Figure 13: Example of gamma fit through 3-monthly precipitation sums for one grid cell.

To verify whether or not the time-series is long enough to calculate the SPI, we have fitted a gamma distribution through the 3-monthly precipitation sums of one grid-cell within the basin

(Figure 13). It can be seen that the fit is reasonably good, except for precipitation sums between 100 and 200 mm.
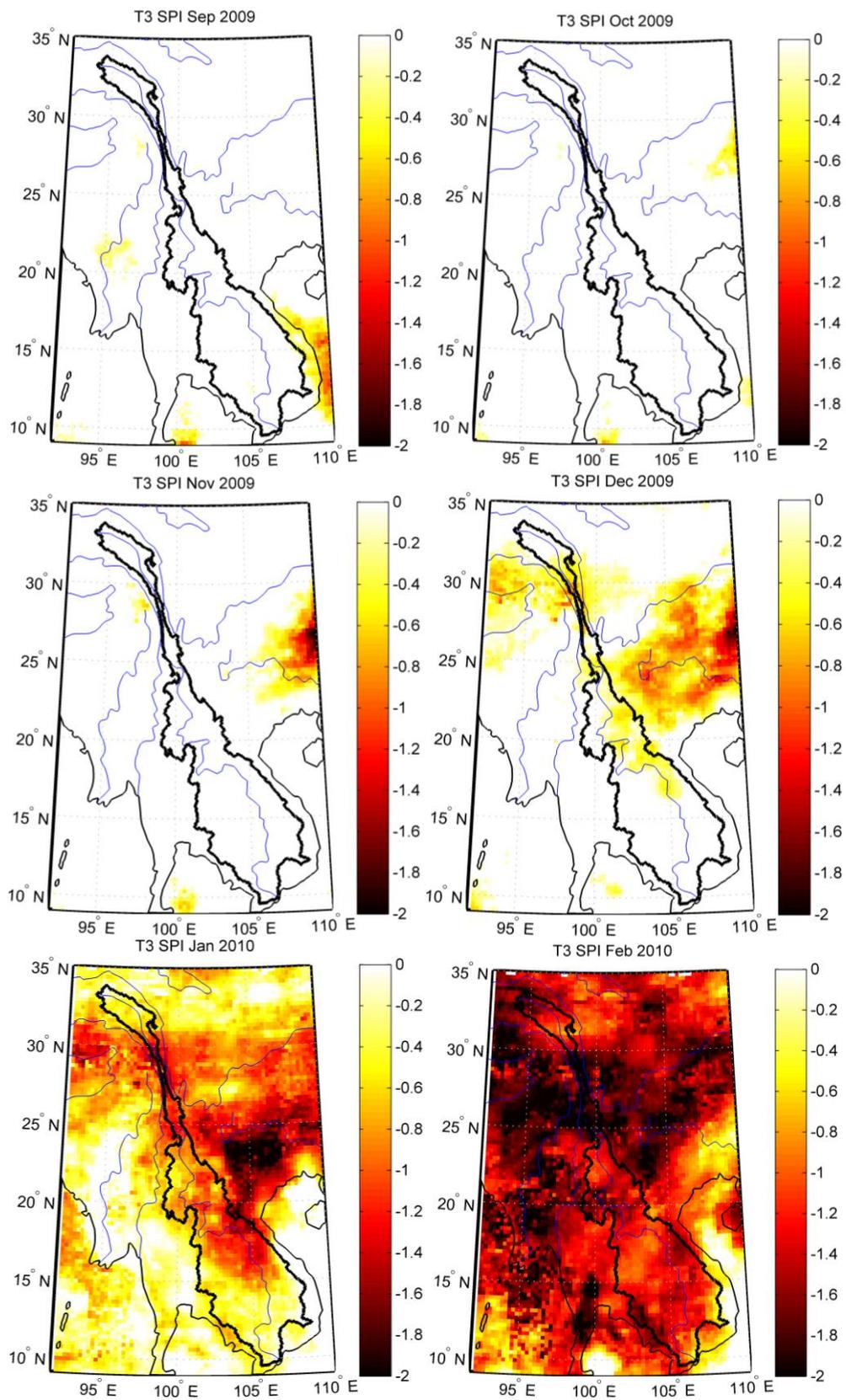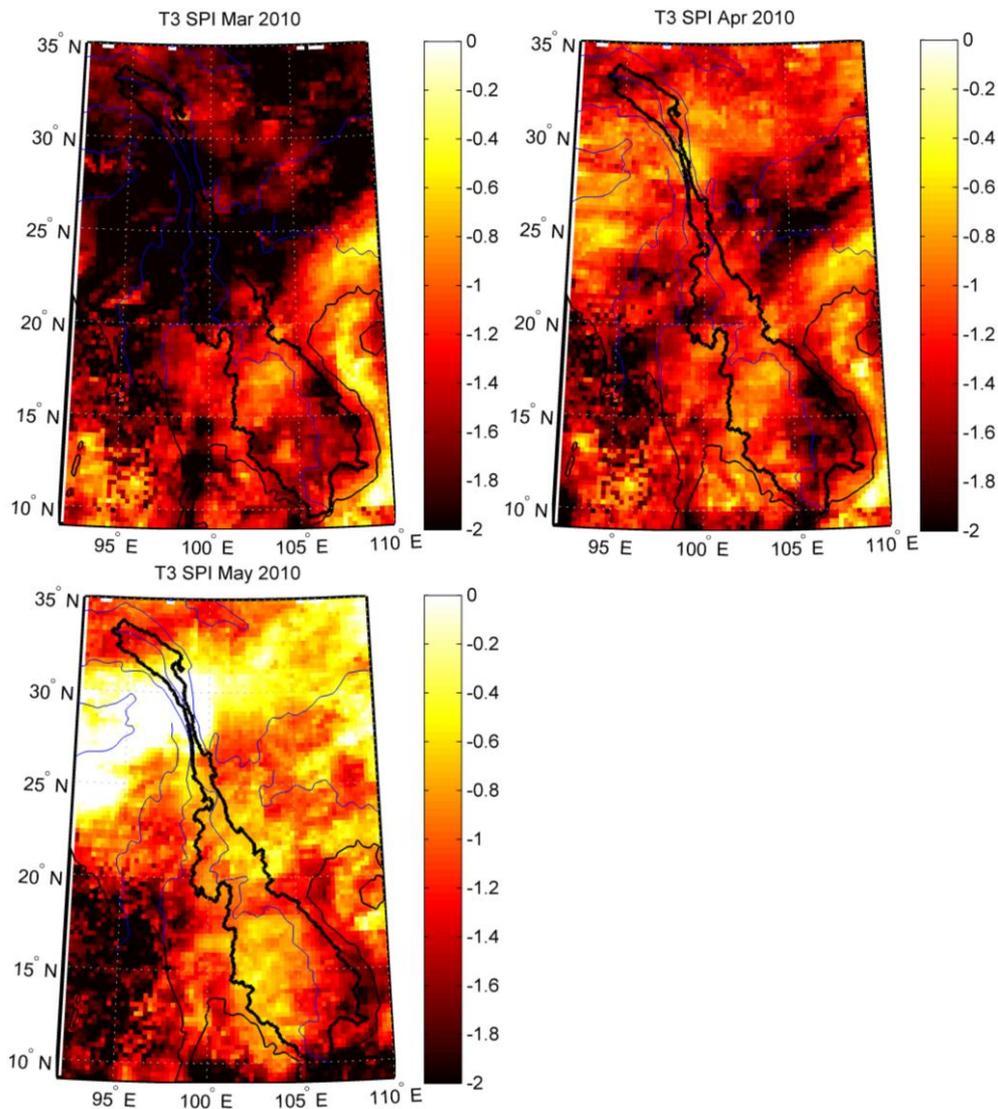
Figure 14: Standardized Precipitation Index (SPI) for September 2009 through May 2010 with a time scale of 3 months (T3).

In this study the SPI has been calculated for time-scales of 3 and 6 months. Figure 14 shows the spatial SPI for a time-scale of three months for September 2009 through May 2010. To quantify the severity of drought, we have used the indicators from McKee et al. (1993) (Table 5). As can been seen from Figure 14, a mild drought starts in December 2009 in the middle of the basin. In January 2010 the largest part of the basin has a moderate drought. Then in February through April, the largest part of the basin is exposed to a severe or extreme drought.

Table 5: SPI drought indicators (McKee et al., 1993).

SPI Value	Drought Category
0 to -0.99	Mild drought
-1.00 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
≤-2.00	Extreme drought

The SPIs can be averaged over the area of interest to get an idea of the areal SPI. For this study we have averaged the SPIs over the entire area and the results for the 3-monthly time-

scale are plotted in Figure 15 for each month. From this figure we can conclude that problems start to occur from January on, with the most severe drought in March 2010.
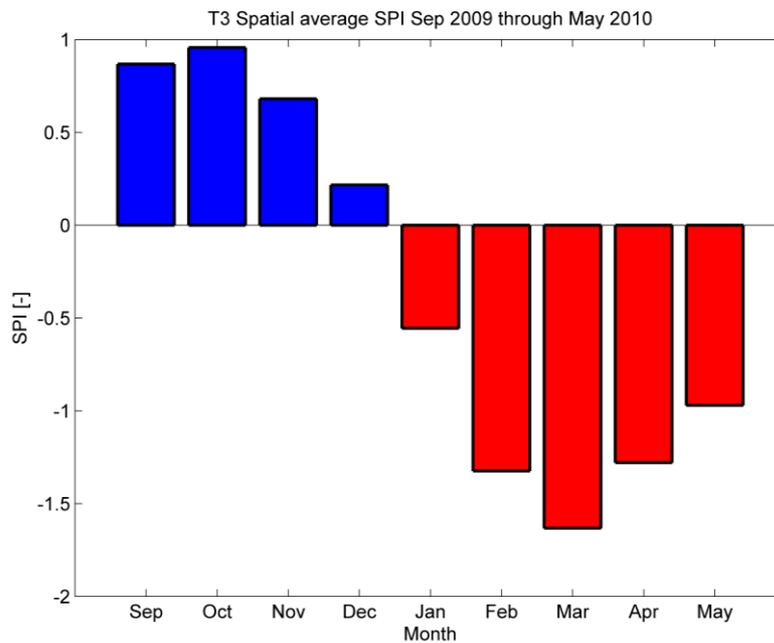

Figure 15: Spatial average SPI for September 2009 through May 2010 with a time scale of 3 months.

Figures for the SPI with a 6-monthly time-scale can be found in Appendix 2. We see that the precipitation deficit starts to develop in a later stage for the 6-monthly time-scale. This is a logical result of the fact that 6-monthly sums are taken into account, so that the probability of a 6-monthly sum below the median is much smaller. Considering the spatial average 6-monthly SPI, it is noticed that a mild drought is developing in February 2010 instead of in January 2010. The severe drought is now shown during May 2010 instead of March 2010. If we consider the spatial SPI for the 6-monthly time-scales, then we see a mild drought starting to develop in January 2010 in the middle of the basin. From March onwards we notice a severe drought in the northern and centre part of the basin, while the southern part is exposed to a mild drought. Then in April there is an extreme drought in most of the basin, while the southern part suffers from a moderate to severe drought. Finally in May most of the basin is exposed to an extreme drought, while the northern part is back to a mild drought.

3.1.3 Moisture Availability Index

As mentioned in Section 2.2.3, the Moisture Availability Index (MAI) is calculated by dividing the precipitation by the reference evapotranspiration. In the current study we have calculated the MAI on a monthly time-scale for September 2009 through May 2010. The evapotranspiration has been calculated using the method of Hargreaves (Hargreaves et al., 1985). To calculate the evapotranspiration the daily average, daily minimum and daily maximum temperature was needed. We used the NCEP/NCAR Reanalysis[2] data. The data are downscaled to a resolution of 0.25 degrees (same as TRMM), using spline interpolation in ArcGIS. Finally the data were aggregated to a monthly evapotranspiration and precipitation value.

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[2] http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surfaceflux.html

In the current study, the MAI was calculated for the months September 2009 through May 2010, as well as for the average of the period September 2009 through May 2010. Figure 16 shows the spatial average MAI for the entire Mekong River Basin for September 2009 through May 2010 with respect to the same months averaged over the years 2000-2010. A MAI smaller than 1, indicates that there is more evapotranspiration than precipitation. We notice a precipitation deficit in November 2009 through April 2010. There is already a precipitation deficit for the period 2000-2010. However, the MAI is significantly smaller in November 2009, December 2009 and February 2010. The MAI for January 2010 is larger than for the average situation. This is caused by a region in which there is above average precipitation (see Appendix 1).
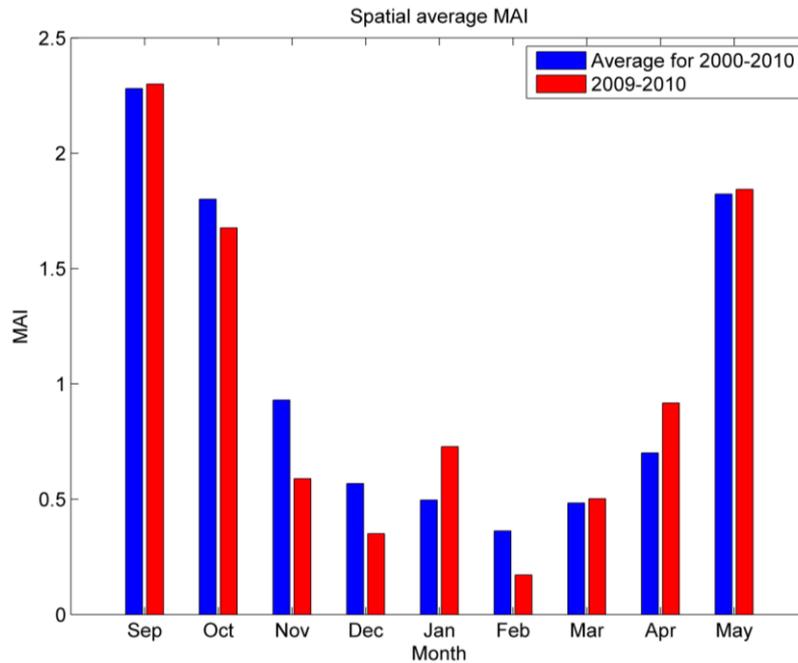
Figure 16: Spatial averaged Moisture Availability Index (MAI) per month for the entire Lower Mekong River Basin. The average MAI over the period Sep 2000 through May 2010 is represented with blue bars. The red bars represent the average MAI for Sep 2009 through May 2010.

Figure 17 represents a spatial comparison of the average MAI for the period 2000-2010 with the MAI for the September 2009 through May 2010. It seems that the area already has a MAI smaller than 1 for the average situation. The MAI for the average period is 0.6-0.7, while September 2009 through May 2010 show MAIs ranging from 0.3 until 0.7, with the lowest values found in the centre of the basin. The lowest MAI values can be found at the east- and west side of the basin. If we consider the individual months (see Appendix 3), then we notice that small MAIs start to develop in September 2009 in the northern part of the basin. This pattern then extends from the northern to the middle part of the basin in October 2009. Then from November 2009 through February 2010, most of the basin is exposed to MAIs ranging from 0 to 0.2. In March 2010 the MAIs remain low throughout the largest part of the basin, while the MAIs in the upstream part are increasing. April 2010 seems to have MAI larger than the average situation, except for the most south-, south-western part.
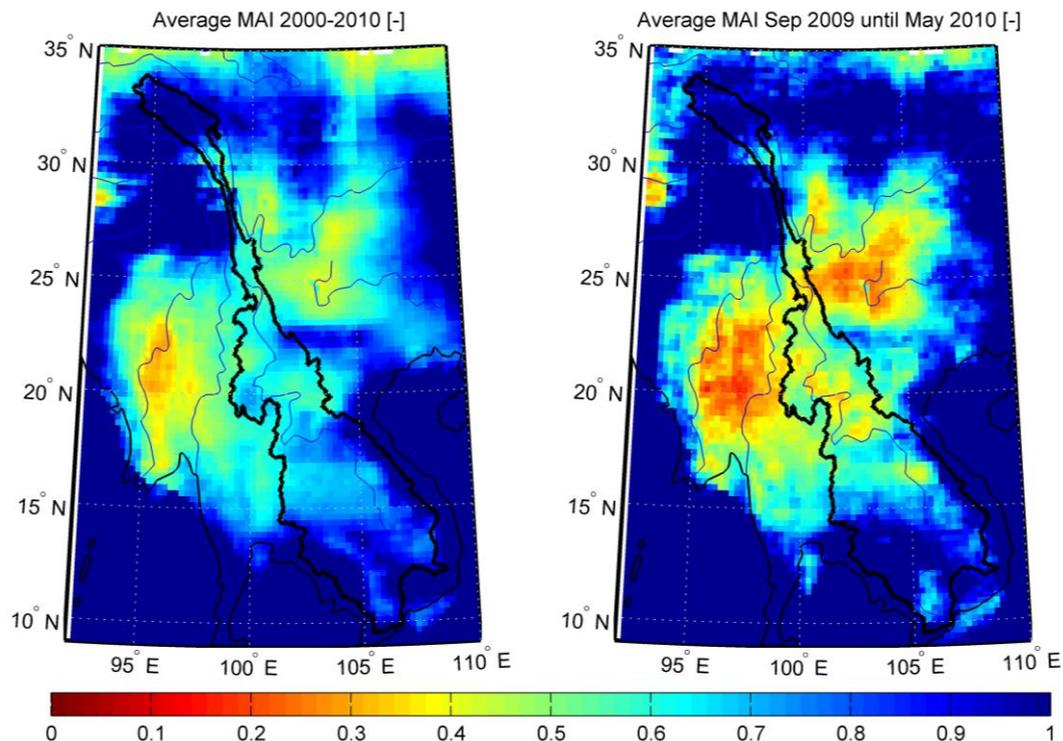
Figure 17: Average MAI for the entire period Sep 2000 through May 2010 (left), and for Sep 2009 through May 2010 (right).

3.2 Agricultural Drought

3.2.1 Normalized Difference Vegetation Index

As was mentioned in Section 2.3.1, the Normalized Difference Vegetation Index (NDVI) is a quantitative measure for the photosynthetic activity in a specific region. It is a value between zero and one, where a higher value (close to one) corresponds to a larger photosynthetic activity than a lower value (close to zero). The NDVI was calculated by the VEGETATION program[3], which is a joint program of Belgium, the European Commission, France, Italy, and Sweden. They use an earth observation sensor on board of the SPOT satellite. The NDVI (http://free.vgt.vito.be) was made available for south-east Asia on a spatial resolution of 0.0089 degrees, which is approximately 1 km.

For this study we have used the NDVI from September 1999 through May 2010. For each month the NDVI has been averaged over the period 1999-2010. Then each month of the period September 2009 through May 2010 is compared with the average for that month, to calculate the anomaly for that month. Results of this analysis are shown in Figure 18 for April 2010. The results for the remaining months are shown in Appendix 4. It seems that during April 2010 there is slightly less photosynthetic activity in some parts of the basin. The photosynthetic activity is already reasonably small for the average situation for April. Therefore the effects for April 2010 are neglectable. Except for September and October, all remaining months hardly show any difference with the average situation for that month. In Appendix 4 it is shown that during September and October 2010 there is less photosynthetic activity in the south-eastern part of

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[3] http://www.spot-vegetation.com/

the basin. For October this can partly be explained by the fact that there is less than average rainfall in this region.
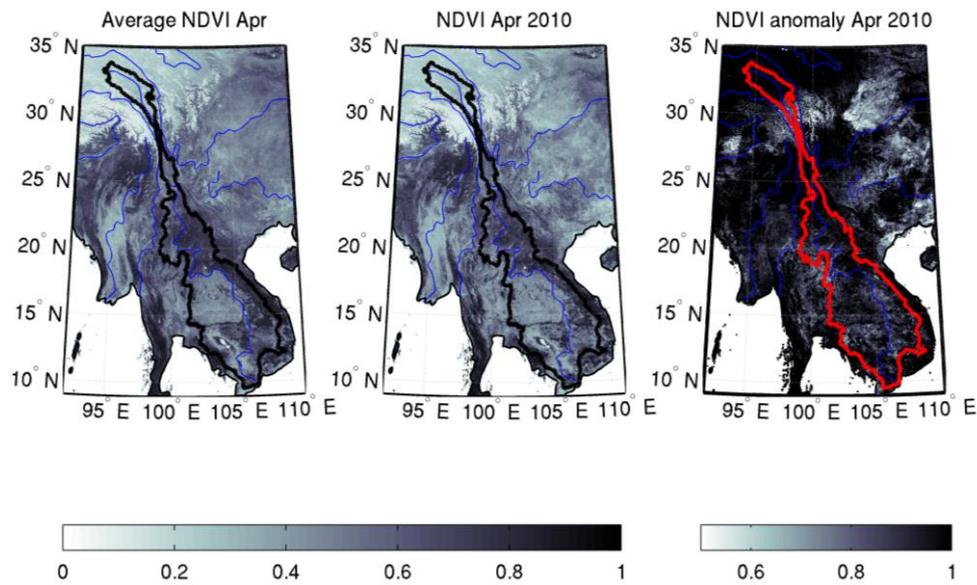

Figure 18: NDVI for April. The left plot represents the average NDVI for 1999-2010. The middle plot represents the NDVI of April 2010. The left plot represents the anomaly between the second and third plot (source: http://free.vgt.vito.be/).

3.2.2   Soil moisture deficits

In the current study, soil moisture deficits are calculated using the anomalies between the soil moisture content of the month of interest, and the average for that month over the period 2004-2010. For the soil moisture data we used the AMSR-E/Aqua level 3 global monthly Surface Soil Moisture Averages[4], with a spatial resolution of 1.00 degree. The data was published by the Goddard Earth Science Data and Information Services Center (GES DISC).

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[4] http://disc.sci.gsfc.nasa.gov/neespi/data-holdings/amsre_avrmo.shtml
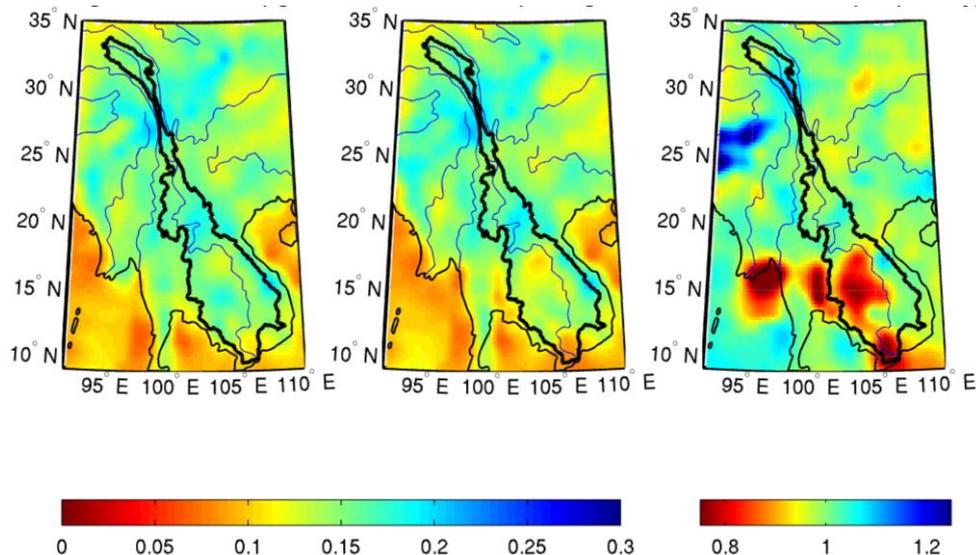
Figure 19: Average soil moisture for May (left), soil moisture in May 2010 (middle), and soil moisture anomaly for May 2010 (right). Units are g/cm³ for the left and middle plot.

For the current study we downscaled the monthly soil moisture data to a spatial resolution of 0.25 degrees, using spline-interpolation in ArcGIS. Figure 19 shows the soil moisture conditions for May. The left plot shows the average soil moisture content for May during 2004-2010, the middle plot represents the soil moisture content for May 2010, and the right plot is the anomaly between the latter two. It needs to be mentioned that for the data above the oceans are not correct and irrelevant. This is due to the fact that in the original data these areas had missing values. For February 2010 no data was available, so this is left out of the analysis. Figures for the remaining months can be found in Appendix 5.

It is shown in Figure 19 that the soil moisture during May 2010 is below average in the South and south-western part of the basin. This is partly related to the low precipitation anomaly. According to the Standardized Precipitation Index (SPI) with 6-monthly time-scale, the largest part of the basin is exposed to an extreme drought during May 2010. This period of extreme drought is reflected in the low soil moisture anomaly, which seems to be most sensitive in the south and south-western part of the basin. The lower soil moisture conditions during May 2010 have a negative effect on the growth of vegetation. This was shown with the below average NDVI in this region (Figure 18). The soil moisture deficit in this region already starts to develop in March 2010 (Appendix 5). Finally, anomalies for soil moisture are low in the southern part from September 2009 through January 2010.

3.3   Hydrological Drought

3.3.1   Stream flow

Monthly streamflow data are used to compare the discharge from September 2009 through May 2010 with the average discharge from September 2000 through May 2010. These data were made available by the MRC for a couple of stations throughout the basin. Figure 20 compares the average monthly discharge for September 2009 through May 2010 with the average for those months over the period 2000-2010.

Discharge Chiang Saen

Discharge Luang Prabang

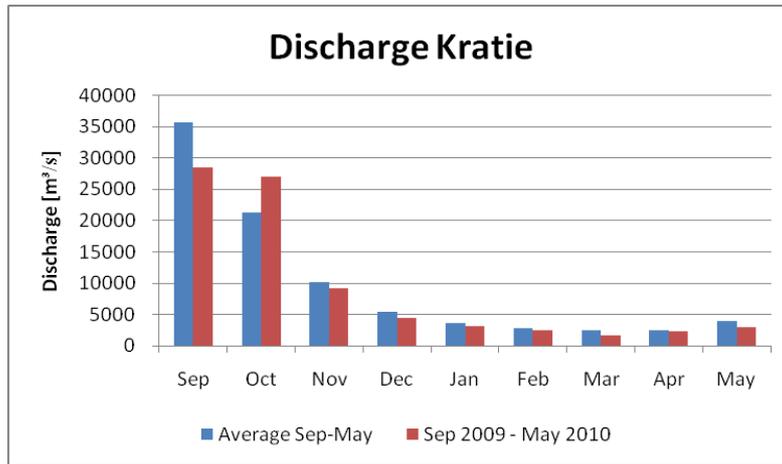Discharge Vientiane

Discharge Pakse
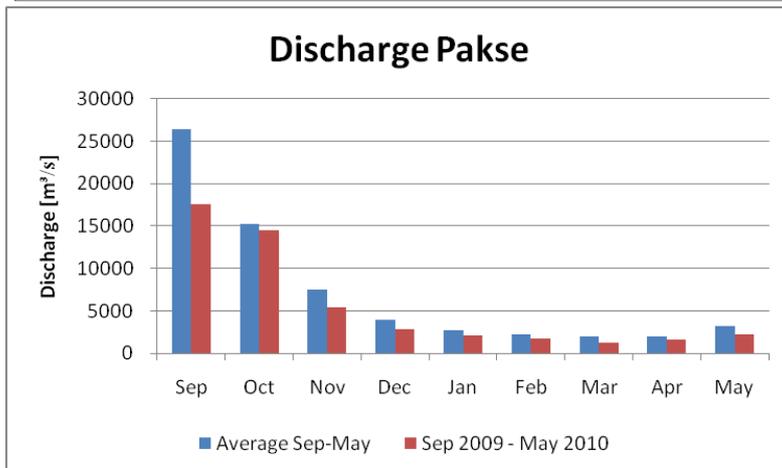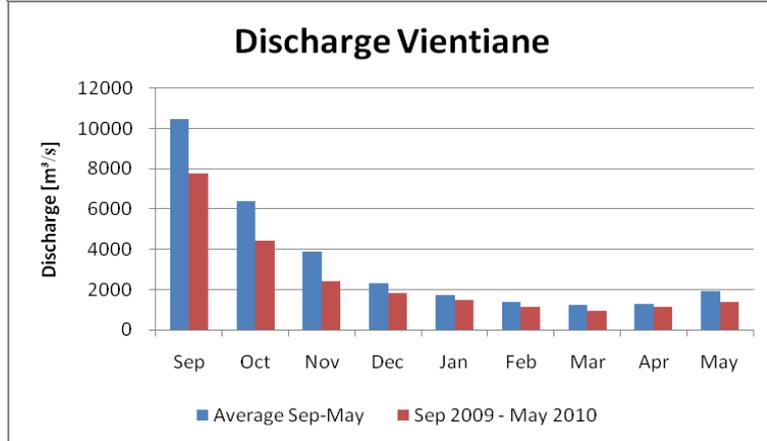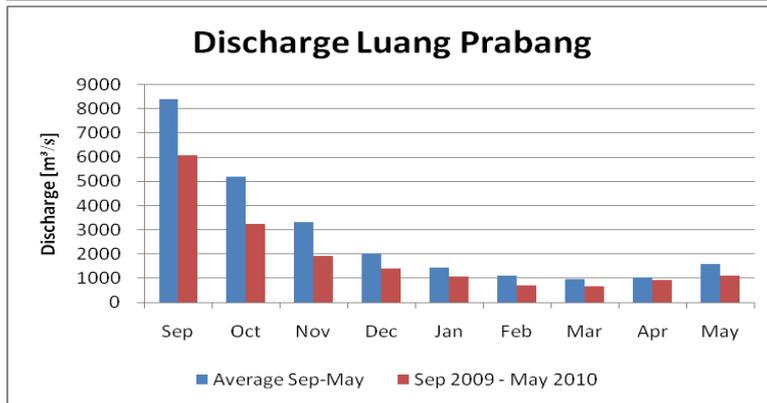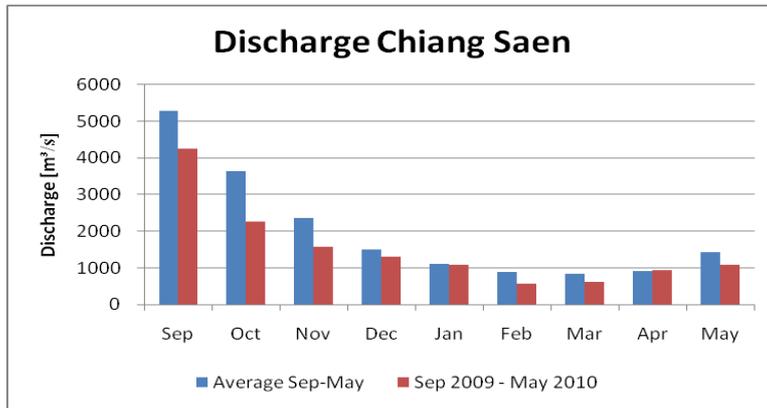
Figure 20: Average monthly discharges for a couple of discharge measurement stations throughout the basin. The plots are ordered from upstream to downstream.

From this figure it is clear that the discharge for the period of interest is below average for all stations during all months, except for Kratie during October. This can be explained by the fact that in September and October there was above average precipitation in and upstream of Kratie. The decrease in discharge is most significant during September. For Kratie, for example, the discharge decreases with 8000 m^3/s during this month. Low discharges during the wet season, like e.g. in September, can have negative effects on the depth and duration of wetland flow inundation, but also have an effect on the inflow of the Tonle Sap Lake.

3.3.2 Reservoirs and lakes

Tonle Sap is the greatest lake in the basin, which is located in Cambodja. The European Space Agency (ESA) River & Lakes uses the ENVISAT satellite to measure water level heights in three locations in Lake Tonle Sap. The locations of these measurements can be found in Figure 21, while the measurements are shown in Figure 22. In this figure the average lake levels for the period September 2000 through May 2010 are compared with the lake levels for September 2009 through May 2010. For the first location no measurements are available for September and May. The second location does not have data for October 2009 and the third location has a gap on February 2010. If we look at the measured water level of each of these locations, then we notice hardly any difference with the average situation. We notice a small increase in water level during October, November and December, while during the remaining months the water level is equal or slightly lower than average. The water levels in the lake depend on the water levels downstream in the Mekong River.
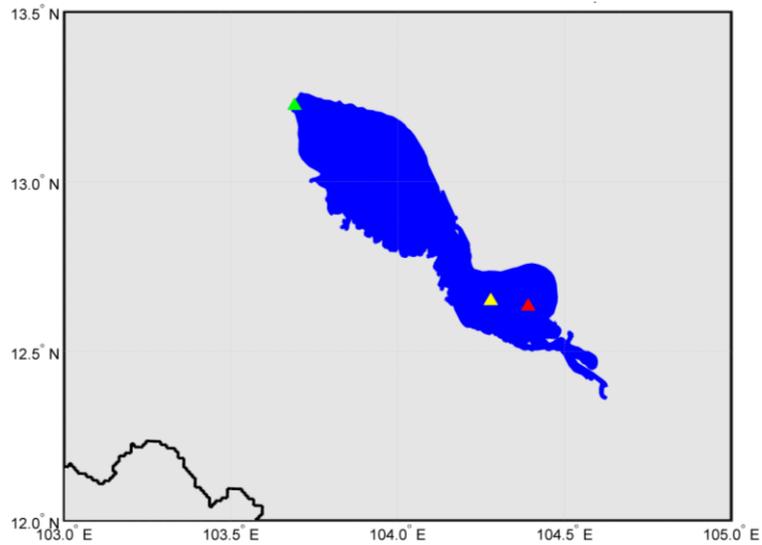
Figure 21: Locations of 3 ENVISAT water level measurements in Lake Tonle Sap (source: European Space Agency (ESA) River & Lake[5]).
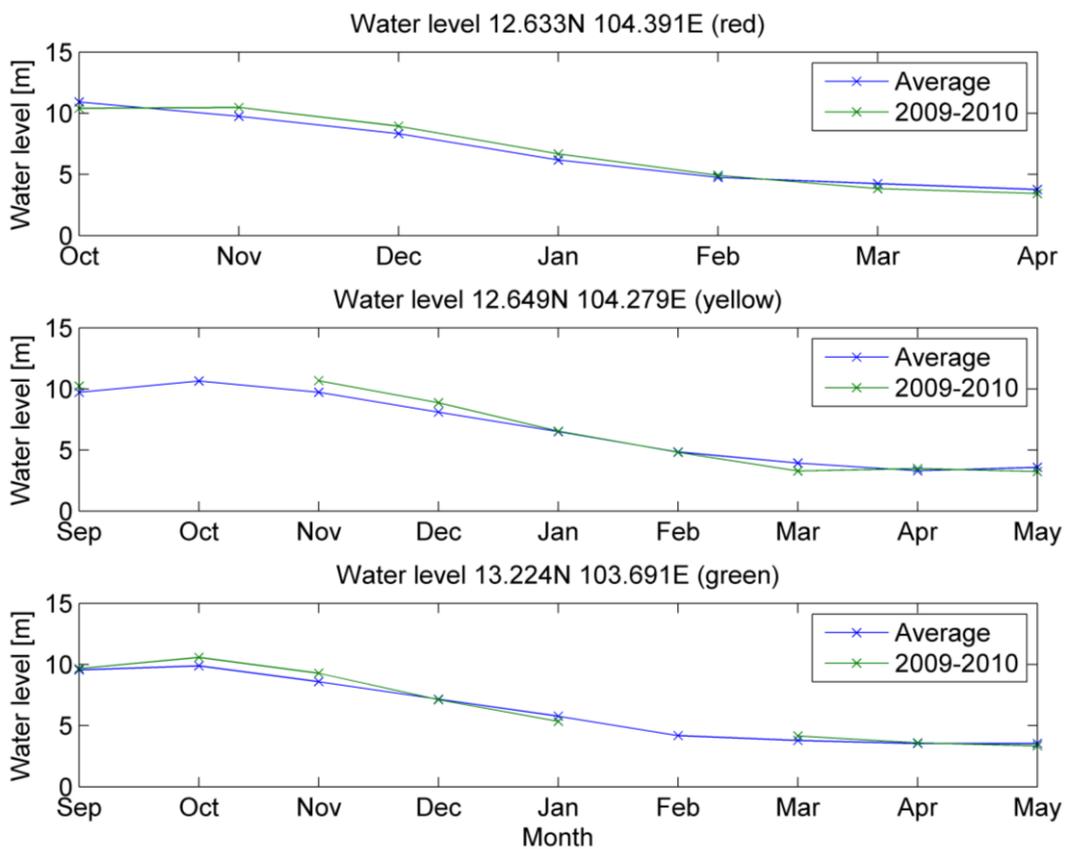

Figure 22: Water levels from Lake Tonle Sap, measured with ENVISAT[5]. Locations are found in Figure 21.

The closest river discharge measurement station with available data is Kratie. During October this station measures above average discharge (Figure 20). The higher discharge causes a higher water level in the Mekong River, and eventually leads to a small increase in lake water

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[5] http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main

level. As can be seen from Figure 20, the discharge in Kratie during January through May is slightly below average. Therefore the lake levels are hardly affected during these months.

4 Drought risk mapping in the Mekong Basin

4.1 Drought risk mapping

The risk of a drought is the probability of harmful consequences, or expected losses resulting from interactions between hazards and vulnerable conditions (Shahid et al., 2008). Therefore, a conceptual approach to drought risk mapping can be broken down into a combination of the hazard and vulnerability. Similar to other natural hazard risks, drought risk depends on a combination of the physical nature of drought and the degree to which a population or activity is vulnerable to the effects of drought (Shahid et al., 2008). To study the risk of drought, therefore, it is essential to study the frequency, severity, and spatial extent of drought, as well as the socioeconomic ability of the region to anticipate and cope with the drought. As mentioned earlier, drought risk mapping can be broken into a combination of hazard and vulnerability:

$$DRI = DHI * DVI$$

Equation 2: Calculation of the Drought Risk Index (DRI) (Blakie et al., 1994).

Where:
DRI = *Drought Risk Index;*
DHI = *Drought Hazard Index;*
DVI = *Drought Vulnerability Index;*

4.2 Quantification of drought risks

To quantify the risk of drought in the Mekong river basin, we applied Equation 2. For this study we have defined several Drought Hazard Indexes and Drought Vulnerability Indexes:

Drought Hazard Indexes:
- Average yearly precipitation sum October through May (HI_1);
- Coefficient of variation (CV) of yearly precipitation sums during October through May (HI_2);
- Average yearly Normalized Difference Vegetation Index (NDVI) during October through May (HI_3);
- CV of yearly NDVIs during October through May (HI_4);

Drought Vulnerability Indexes:
- Population density (VI_1);
- Gross Domestic Product (GDP) per capita (VI_2);
- Land use (VI_3);
- Distance to river (VI_4);

Drought risk mapping is performed on a spatial resolution of 0.05 degrees, which is approximately 5 km.

4.2.1 Drought Hazard Index

The DHI is calculated using the four hazard indexes as defined in Section 4.2:

$$DHI = \frac{HI_1 + HI_2 + HI_3 + HI_4}{4}$$

Equation 3: Calculation of the Drought Hazard Index (DHI).

The first hazard index is the average of the yearly precipitation sums during October through May. The lower the average precipitation sum is, the higher the hazard index will be. Areas which are prone to low precipitation values are more hazardous. For each grid cell, the value is scaled to a value between zero and one:

$$HI_1 = 1 - \left(\frac{value - \min(values)}{\max(values) - \min(values)} \right)$$

Equation 4: Scaling of average precipitation Hazard Index between 0 and 1.

Where: *value* =   *average precipitation sum;*
              values =   *all average precipitation sums in the basin;*

The hazard index map for the average yearly precipitation can be found in Appendix 6: Hazard Index maps. Based on this map, it can be seen that the hazard is highest in the northern part of the basin and lowest in the southern part of the basin.

The second hazard index is the CV of average yearly precipitation sums, based on the period October through May. The CV is calculated by dividing the standard deviation of yearly precipitation sums by the average of yearly precipitation sums. Areas with large CV values indicate areas with a large year-to-year variation in precipitation. Therefore, a high CV indicates a high hazard. Each grid cell is again scaled between zero and one:

$$HI_2 = \left(\frac{value - \min(values)}{\max(values) - \min(values)} \right)$$

Equation 5: Scaling of CV of precipitation Hazard Index between 0 and 1.

Where: *value* =   *CV of average precipitation sums;*
              values =   *all CVs of precipitation sums in the basin;*

The hazard index map for the CV of average precipitation sums can be found in Appendix 6: Hazard Index maps. It is shown that especially the southeastern and middle parts of the basin have the highest hazards. This means that in these regions the yearly precipitation sum during October through May can be significantly lower than the average.

The third hazard index is the average of yearly NDVIs, based on the period October through May. Regions with low NDVIs indicate areas with low photosynthetic activity, thus less vegetation growth. Therefore, regions with low NDVIs are more hazardous to droughts. Each grid cell is scaled between zero and one using a similar equation as Equation 4. The hazard index map for the average NDVIs is shown in Appendix 6: Hazard Index maps. It can be noticed that the northern part of the basin has the highest NDVI hazard index. It should be taken in mind that this is a mountainous area with barely any vegetation. High hazard indexes are also found in the central and south, southwest part of the basin. The high hazard index for Lake Tonle Sap can be neglected, because this is of course an area with no vegetation at all.

The last hazard index is the CV of average yearly NDVIs. Areas with large CV values indicate areas with a large year-to-year variation in photosynthetic activity. Each grid cell is scaled between zero and one, using a similar equation as Equation 5. From the hazard index map of CVs (Appendix 6: Hazard Index maps) it can be concluded that the highest NDVI hazards are found in the northern part of the basin. In addition to this, high hazards for the NDVI are found in the south, and southwestern part of the basin, with exception of Lake Tonle Sap.

Based on the four individual hazard indexes we calculate the DHI based on Equation 3. The result is a Drought Hazard Index map (Figure 23). This map shows that the drought hazard is highest in the northern and south, southeastern part of the basin. Also the central part of the basin is quite hazardous to droughts.
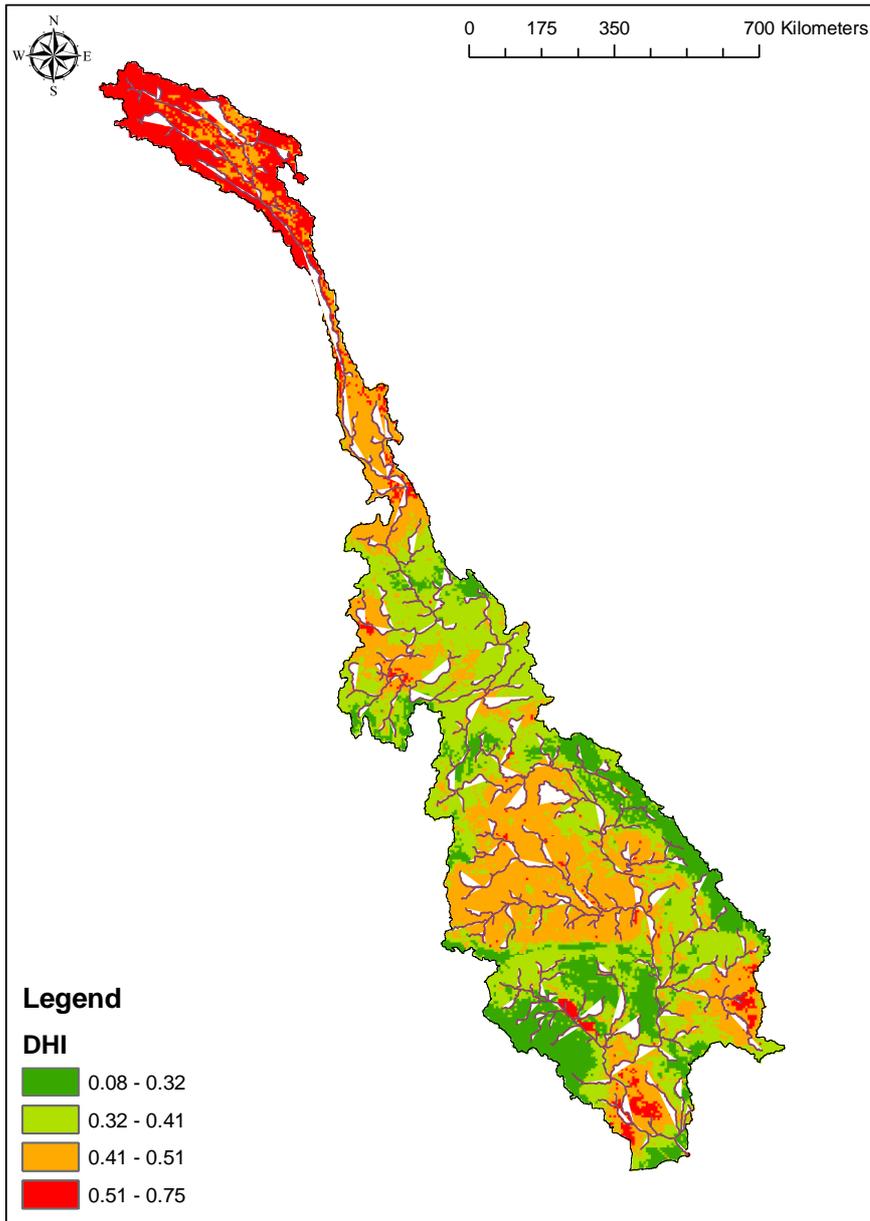
Figure 23: Drought Hazard Index map. A higher value corresponds to a higher hazardous area.

4.2.2   Drought Vulnerability Index

The Drought Vulnerability Index (DVI) is calculated using the four indexes as defined in Section 4.2:

$$DVI = \frac{VI_1 + VI_2 + VI_3 + VI_4}{4}$$

Equation 6: Calculation of Drought Vulnerability Index (DVI).

The first vulnerability index is the population density. For the population density we used data from the Netherlands Environmental Agency[6]. They have downscaled population data based on the IPCC-SRES scenarios[7]. For this study we use the average population density between 2010 and 2015. Areas with high population densities are more vulnerable to droughts. For each grid cell, the population density is scaled to a value between zero and one:

$$VI_1 = \frac{value - \min(values)}{\max(values) - \min(values)}$$

Equation 7: Scaling of population density between 0 and 1.

Where: *value*   =   *population density;*
              values =   *all population densities in the basin;*

The vulnerability index maps are shown in Appendix 7: Vulnerability Index maps. Based on the population vulnerability index, it is noticed that vulnerabilities are largest in the central part of the basin. Besides this region, there are smaller areas with high vulnerabilities in the southern and more northern part of the basin.

The second vulnerability index is the Gross Domestic Product (GDP) per capita. Again we use (downscaled) data from the Netherlands Environmental Agency. Areas with a small GDP are more vulnerable to droughts than areas with high GDPs. Therefore, for each grid cell the GDP is scaled to a value between zero and one:

$$VI_2 = 1 - \left(\frac{value - \min(values)}{\max(values) - \min(values)} \right)$$

Equation 8: Scaling of GDP between 0 and 1.

Where: *value*   =   *GDP per capita;*
              values =   *all GDPs per capita in the basin;*

According to the vulnerability index of the GDP in Appendix 7: Vulnerability Index maps, the largest area of the basin is vulnerable to drought. This is logically highly correlated with areas with small population densities.

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[6] http://www.pbl.nl/en/index.html

[7] http://www.pbl.nl/en/publications/2006/DownscalingDriversOfGlobalEnvironmentalChangeScenarios.html

The third vulnerability index is land use. For land use we used data from the European Space Agency[8] (ESA). In their GLOBCOVER[9] project they produced a global land cover map using the ENVISAT environmental satellite. For the purpose of this study, we have created 6 classes based on the land cover map. This map is shown in Figure 24. Land use classes with high vulnerability to drought are given a high index number. The results of this classification are shown in Table 6. The class "Other" involves areas covered with rock, snow/ice, or water bodies. Again these vulnerability indexes are scaled between zero and one, using a similar equation as Equation 7. The map with land use vulnerability indexes is shown in Appendix 7: Vulnerability Index maps. It can be concluded that mainly the central and southern part of the basin are highly vulnerable. These are areas with rainfed or irrigated agriculture.
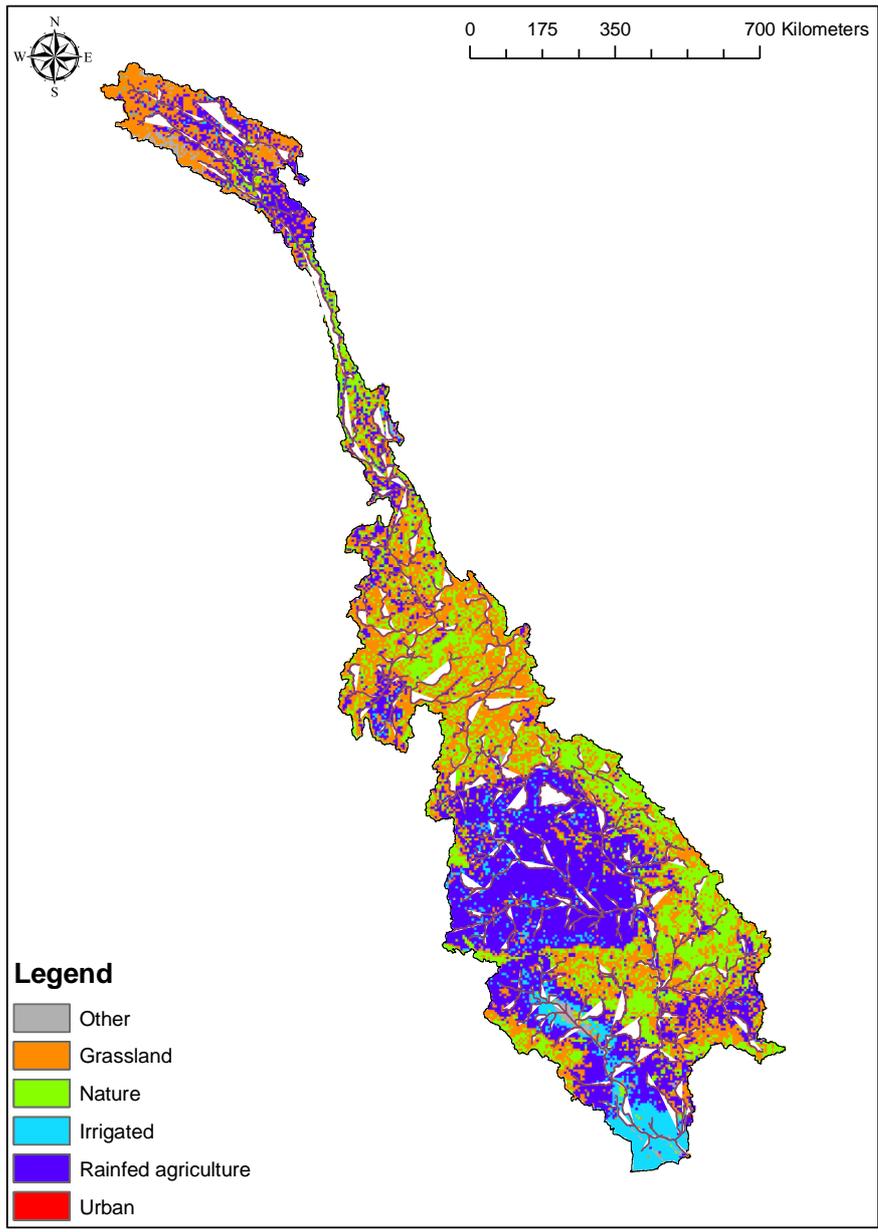
Figure 24: Reclassified land use classes.

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[8] http://www.esa.int/esaCP/index.html

[9] http://www.esa.int/esaEO/SEMGSY2IU7E_index_0.html

Table 6: Indexation of land use classes, based on their vulnerability to droughts.

Land use	Index
Urban	5
Rainfed agriculture	4
Irrigated	3
Nature	2
Grassland	1
Other	0

The final drought vulnerability index is distance to the river. Areas on a long distance from the river are more dependent on precipitation, and thus more vulnerable to drought, than areas which are located on a short distance from the river. Distances from the river are also scaled between zero and one, using a similar equation as Equation 7. The resulting vulnerability index map is shown in Appendix 7: Vulnerability Index maps.

Based on the four drought vulnerability indexes, we calculate the Drought Vulnerability Index (DVI) using Equation 6. The resulting Drought Vulnerability Index map is shown in Figure 25. Based on Figure 25 we conclude that the vulnerability is largest in the central and southern part of the basin. This is mainly caused by the rainfed and irrigated agriculture, and high population densities in these regions.

4.2.3   Drought Risk Index

The DRI is calculated by multiplying the DHI (Figure 23) by the DVI (Figure 25). The DRI map is shown in Figure 26. The classes are derived using the natural break method in ArcMap. It can be concluded that drought risks are largest in the central and south, southeastern part of the basin. The drought risk in the northern part is high due to the large hazard index in this area. Especially the high hazard index for average precipitation and NDVI are high in this region.
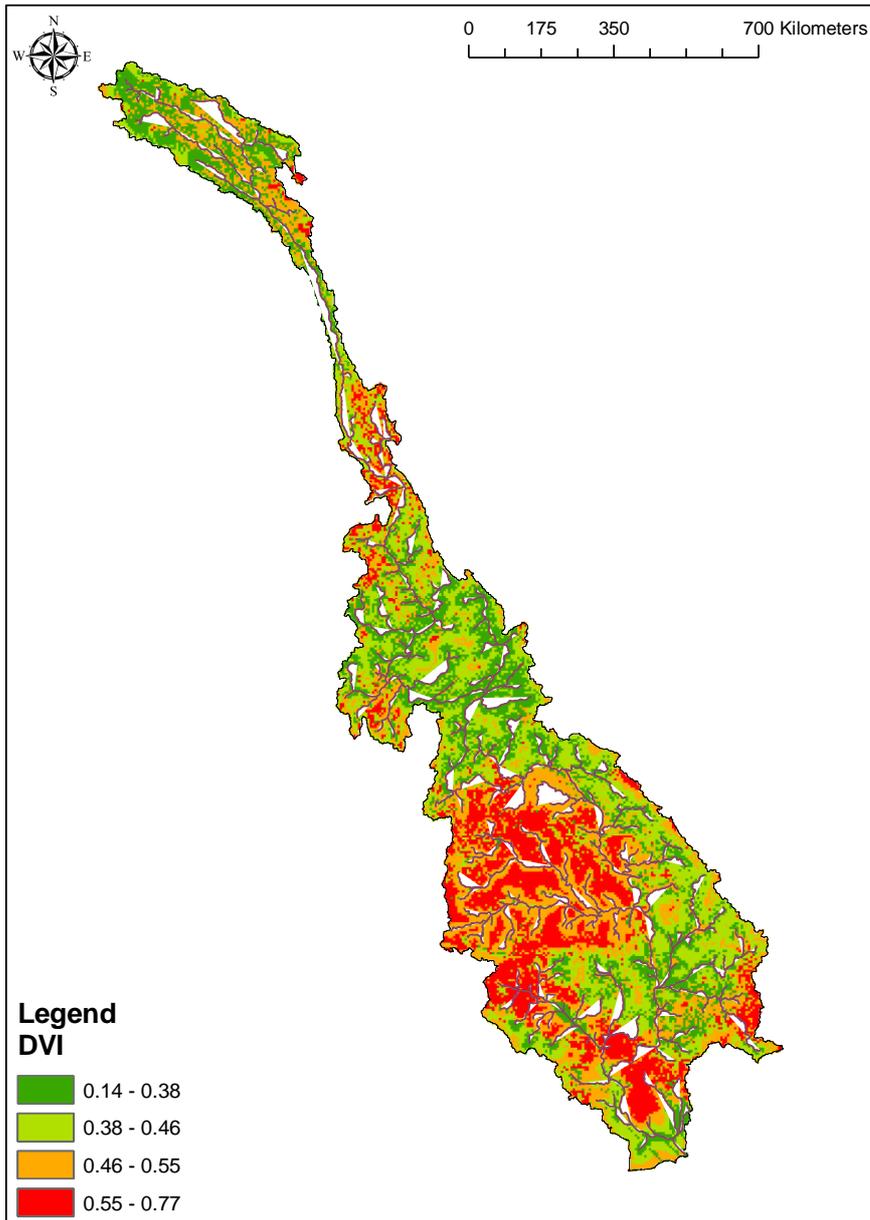
Figure 25: Drought Vulnerability Index map. A higher value corresponds with higher drought vulnerability.
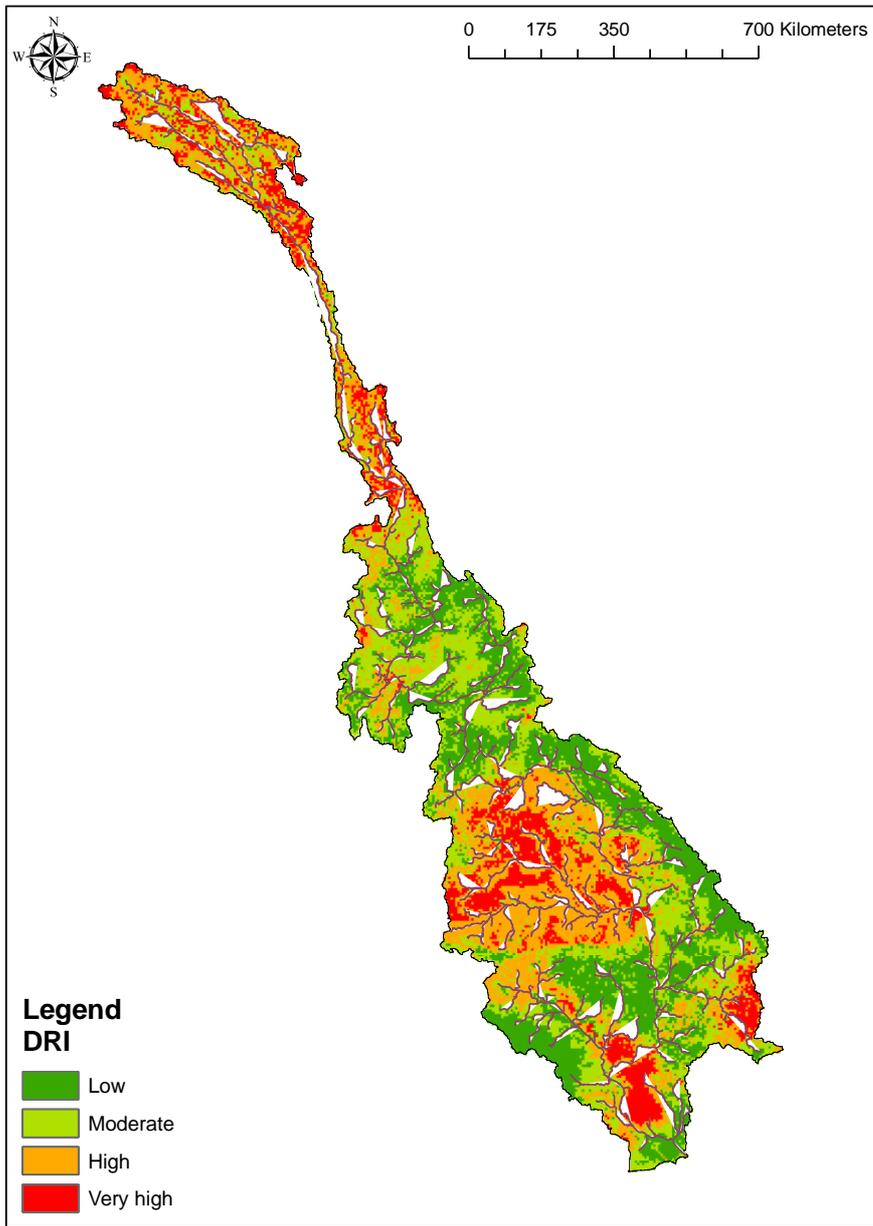
Figure 26: Drought Risk Index map.

5 Conclusions and recommendations

The Mekong River Commission started to discuss on a drought management initiative already in 2006. The severe drought from 2009-2010 demonstrated once again the importance of the issue for people and the environment in the Mekong River Basin. It was therefore decided to place drought again higher on the agenda, all in agreement with the Draft Strategic Plan 2011-2015. It was also decided that a full program would not be the most efficient way in dealing with the topic and it was agreed to develop a Drought Management Initiative (DMI).

This technical report introduces and demonstrates components that can be used for a full drought monitoring and impact assessment program, similar to the flood forecasting centre in Phnom Penn. This report made it very clear that there is however a huge difference between flood and drought. The main issues raised are:
- Impact of drought is of the same magnitude or even higher compared to the impact of floods.
- Procedures set in place for flood management cannot be transferred directly for drought management.
- Drought assessment and alleviation is far more complex than flooding.
- Climate change will increase drought substantially.
- Floods provide many positive services; drought not.
- Drought is a trans-boundary and basin-wide issue.

A framework and associated analysis tools were introduced and demonstrated for the 2009-2010 drought in this report. It is clear that by using a mixture of observations, most of these based on readily available satellite information, will support a drought management program. This framework, revered to as "Drought Monitoring and Impact Assessment Toolbox" (DMIAT) is flexible and can be tailor-made to the need of the user. Moreover, it is very clear that, by the nature of the observations, a drought assessment and analysis program is not extremely complex or costly. Moreover, since droughts develop gradually, early warning and support planning can be done effectively.

The objective of this study was not to develop a complete framework for drought, but only to demonstrate some of the highlights using the 2009-2010 drought as typical example. The Drought Monitoring and Impact Assessment Toolbox (DMIAT) as demonstrated here could form the base for the Mekong River Commission to support the countries in a better preparedness to drought. Further development and refinement of DMIAT, based on the analysis presented here, should be explored.
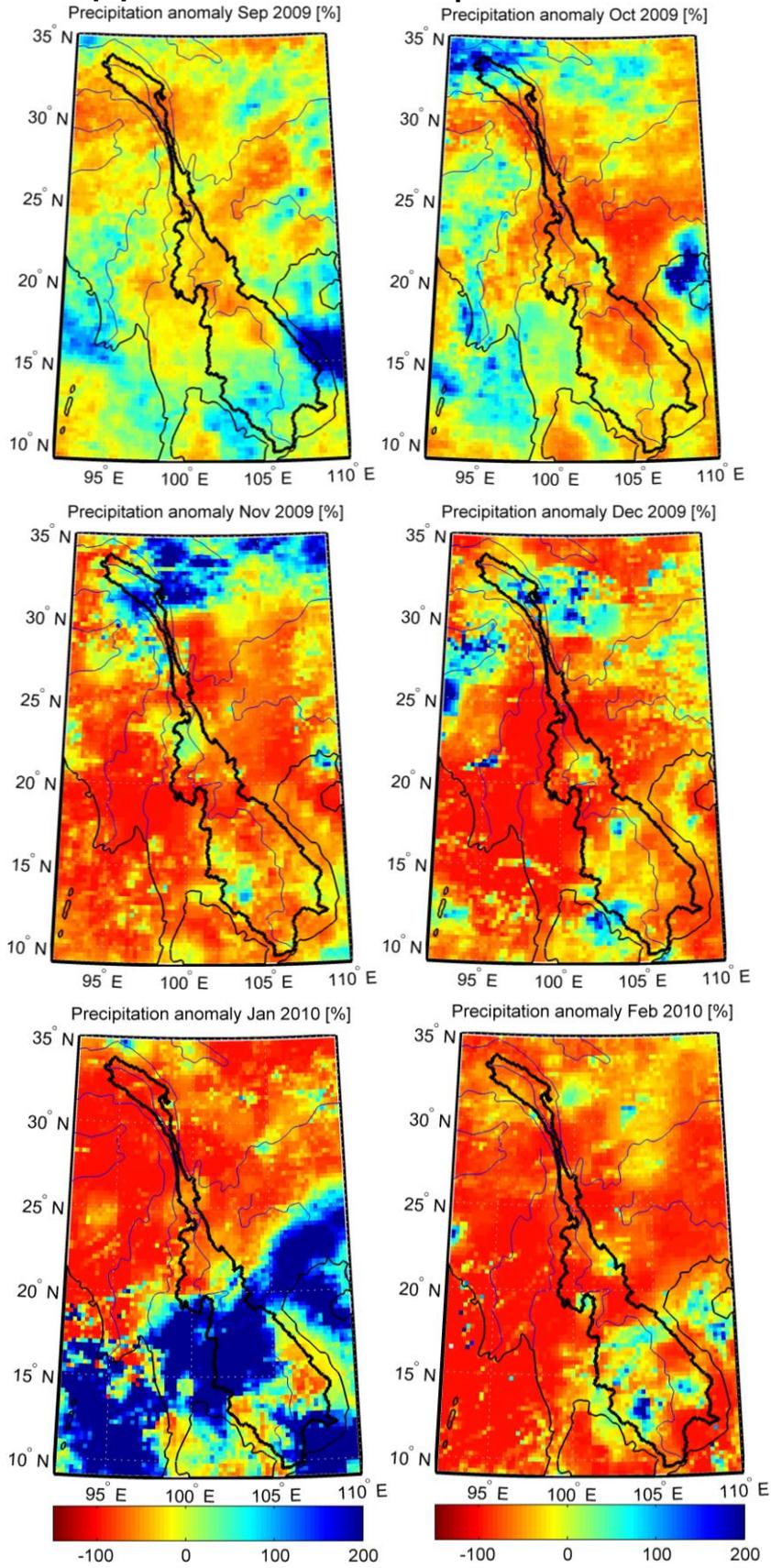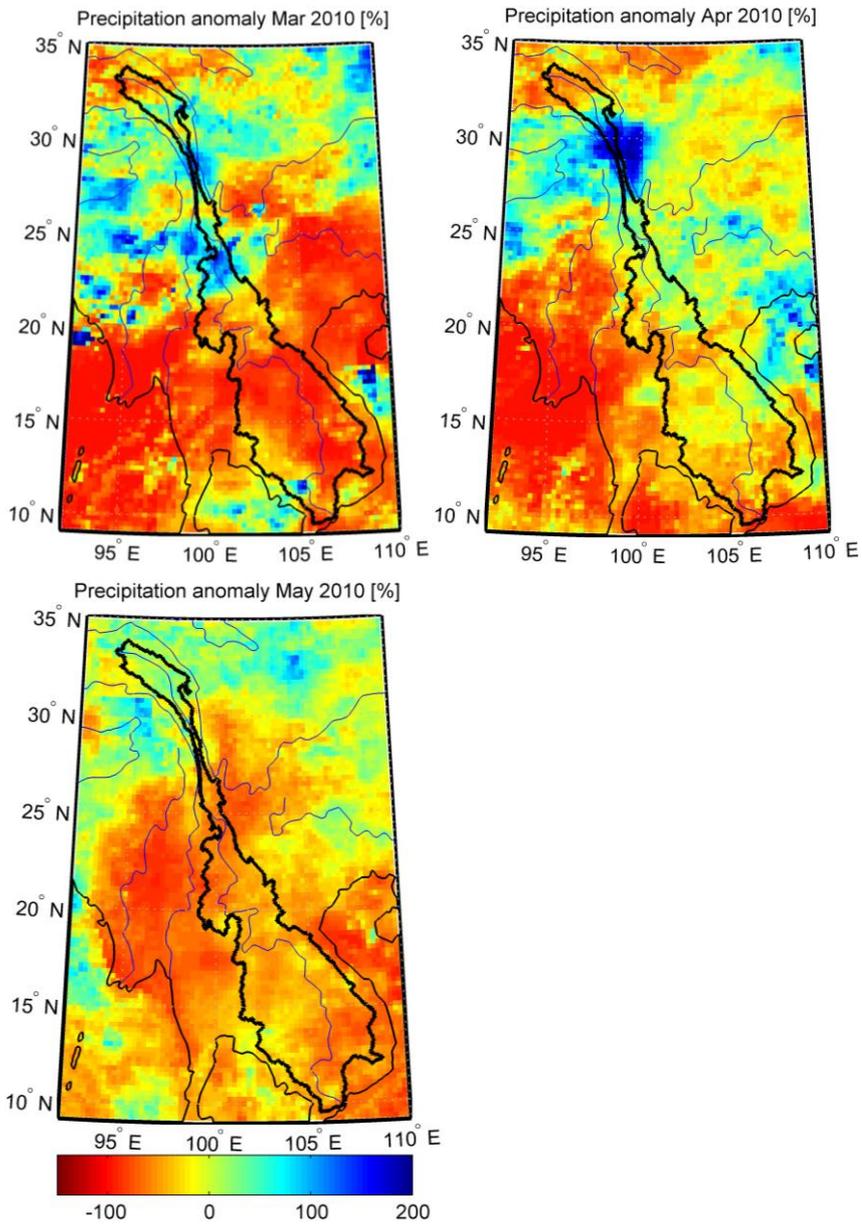
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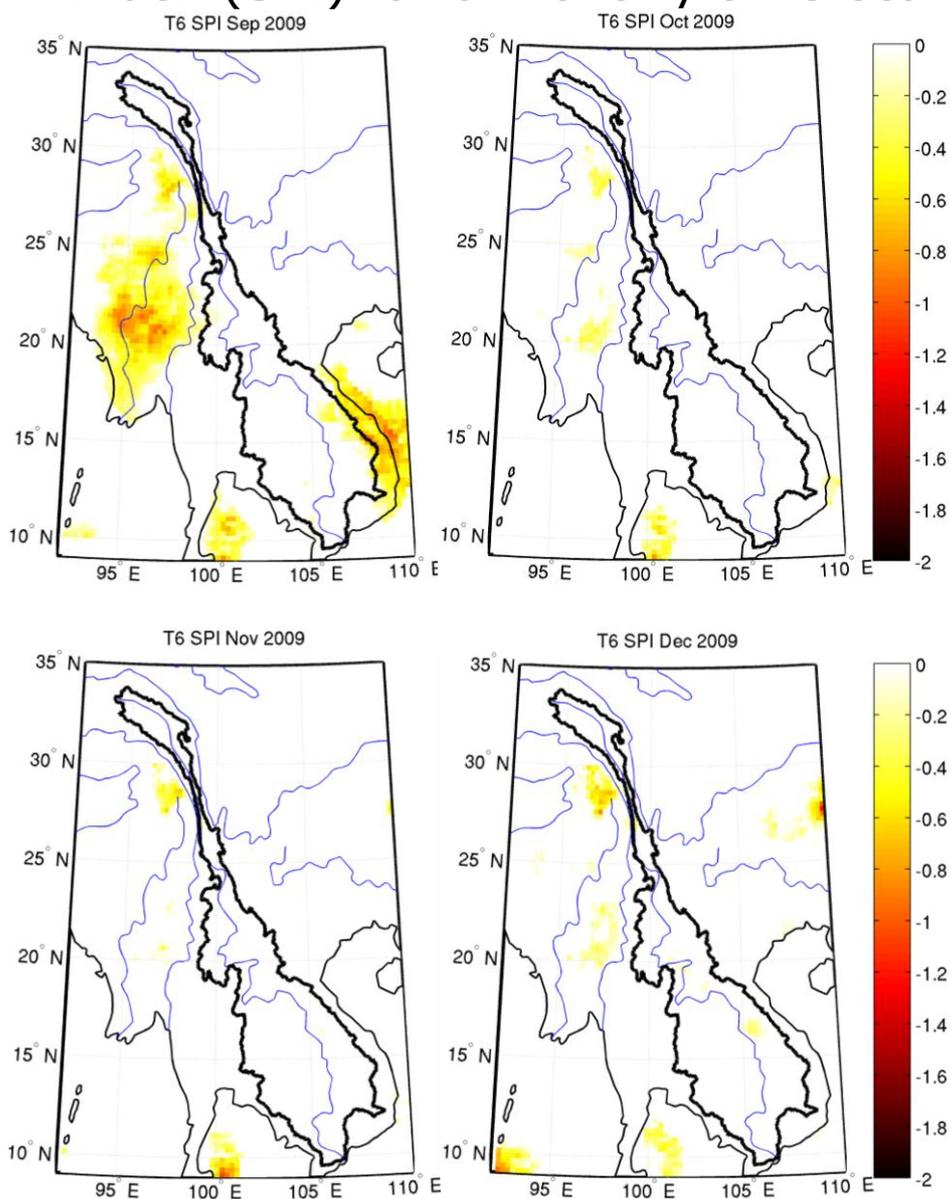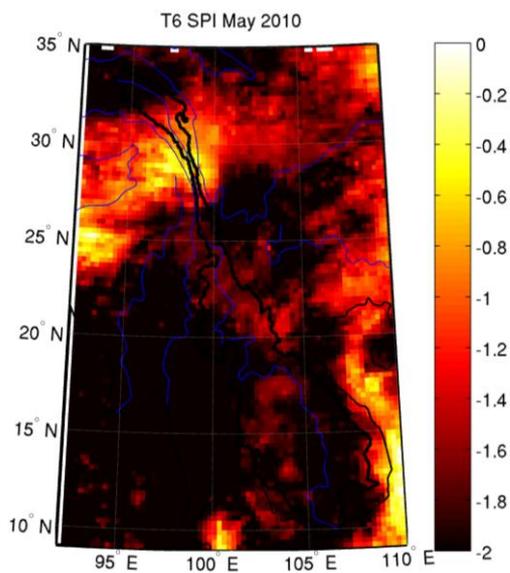Willeke, G., J.R.M. Hosking, J.R. Wallis, and N.B. Guttman. 1994. The National Drought Atlas. Institute for Water Resources Report 94–NDS–4, U.S. Army Corps of Engineers.
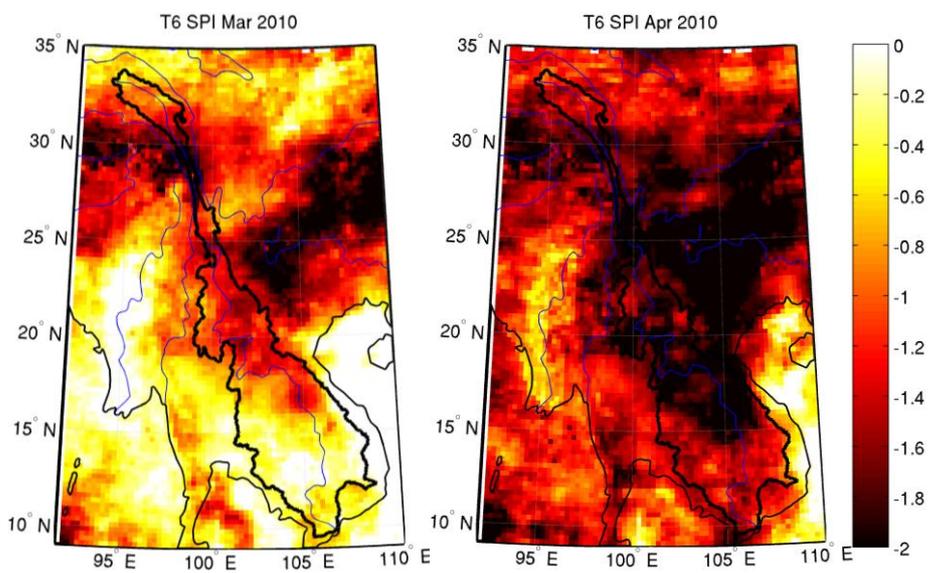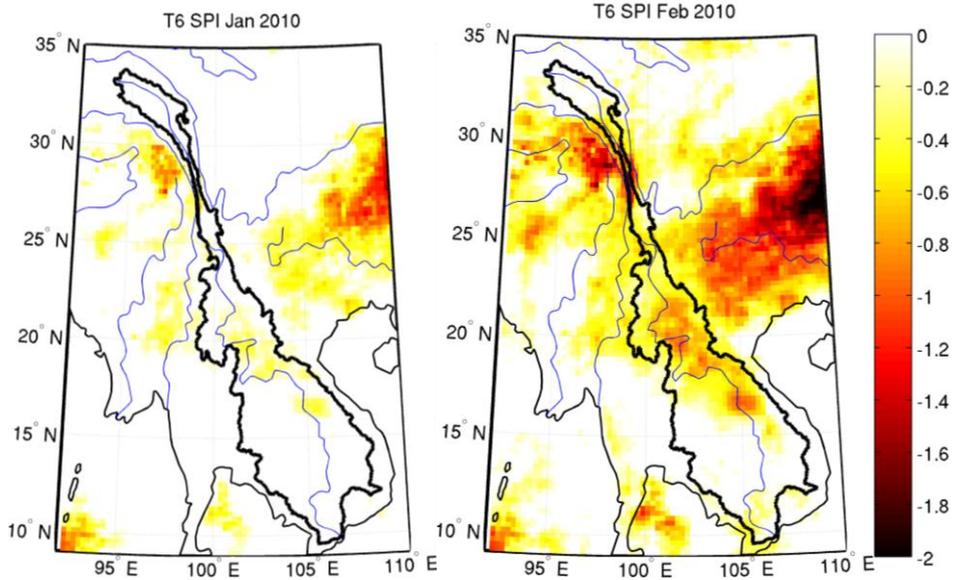
Appendix 1: Precipitation anomalies

Precipitation anomaly Mar 2010 [%]

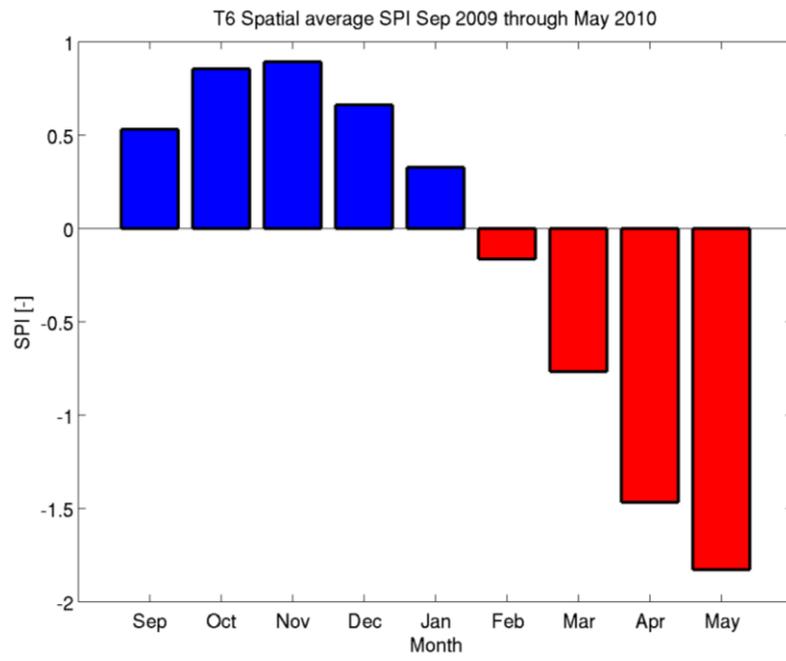Precipitation anomaly Apr 2010 [%]

Precipitation anomaly May 2010 [%]

Appendix 2: Standardized Precipitation Index (SPI) for 6-monthly time-scale

T6 SPI Jan 2010

T6 SPI Feb 2010

T6 SPI Mar 2010

T6 SPI Apr 2010

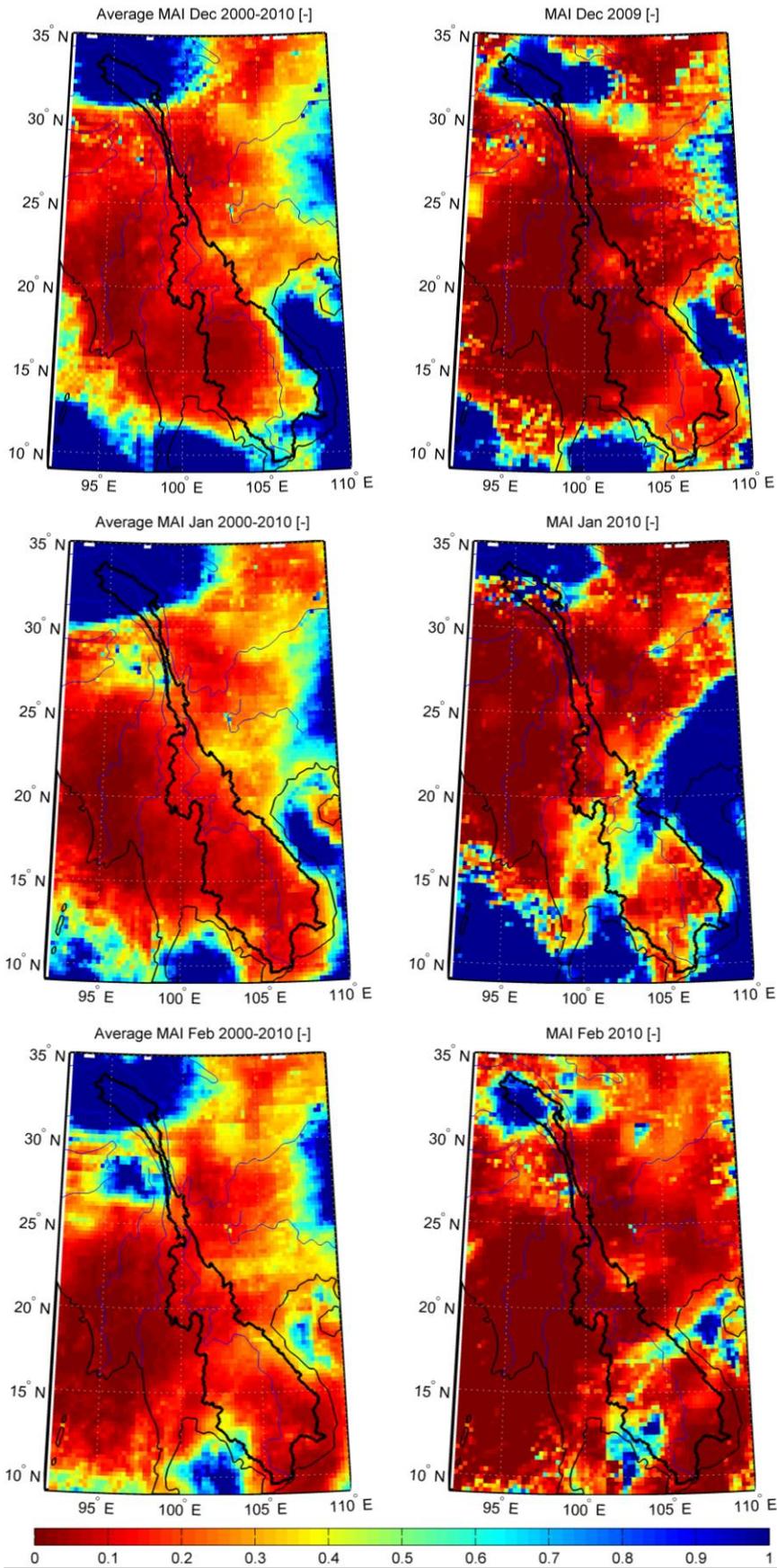T6 SPI May 2010
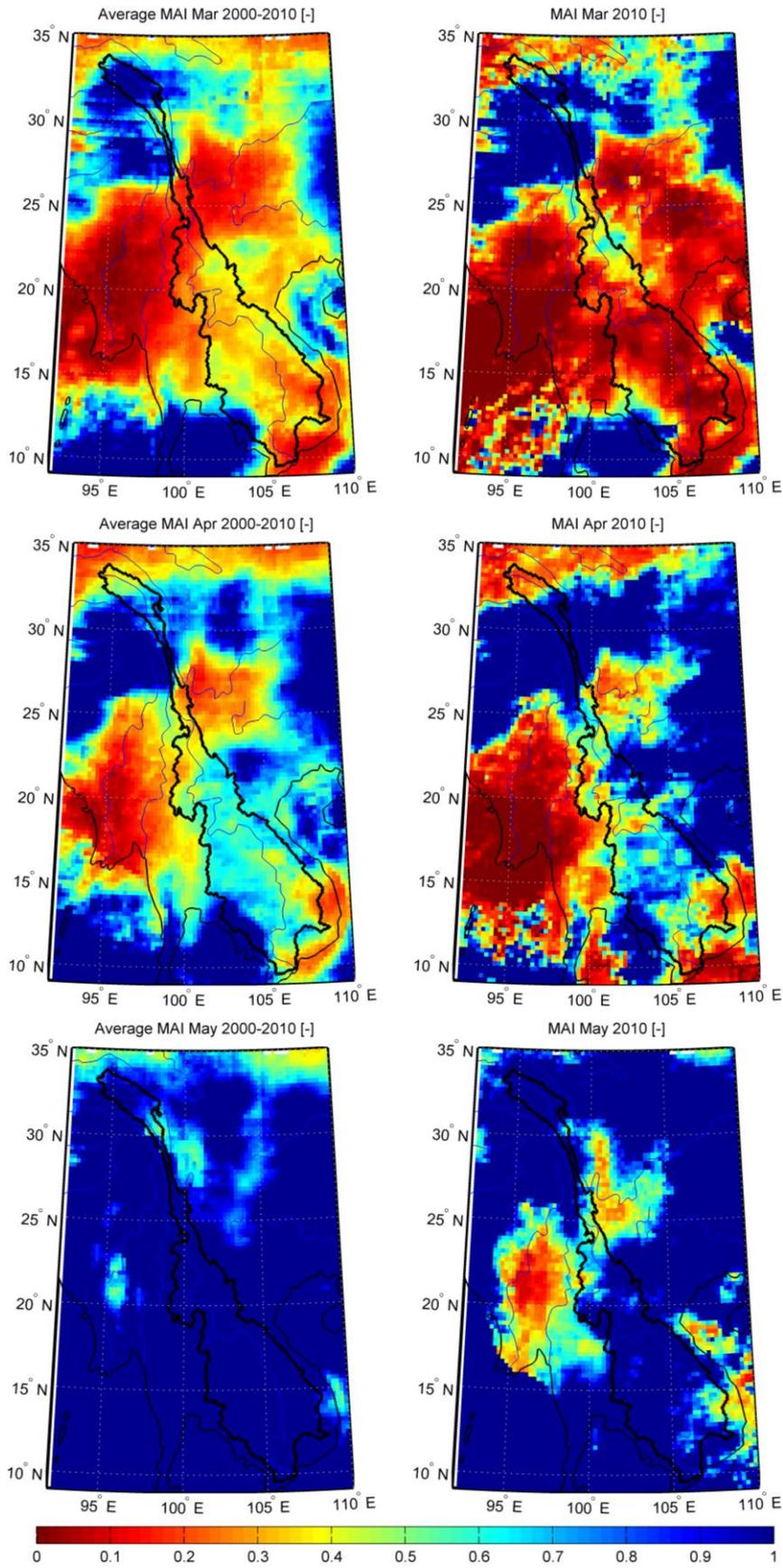
T6 Spatial average SPI Sep 2009 through May 2010

Appendix 3: Moisture Availability Index
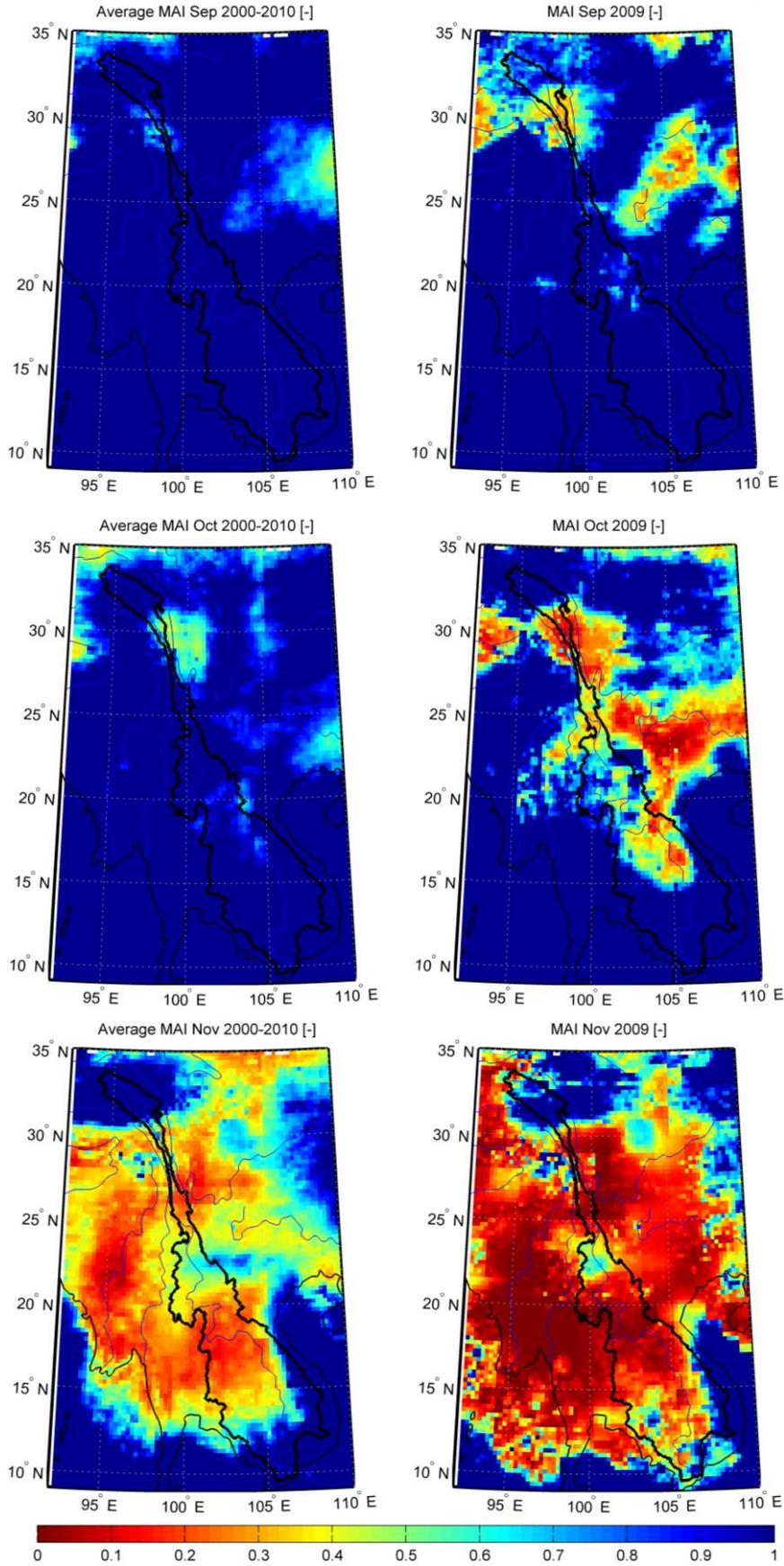
Appendix 4: Normalized Difference Vegetation Index (NDVI)

Average NDVI Jan   NDVI Jan 2010   NDVI anomaly Jan 2010

Average NDVI Feb   NDVI Feb 2010   NDVI anomaly Feb 2010

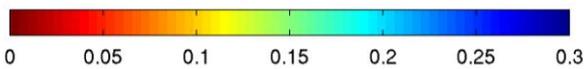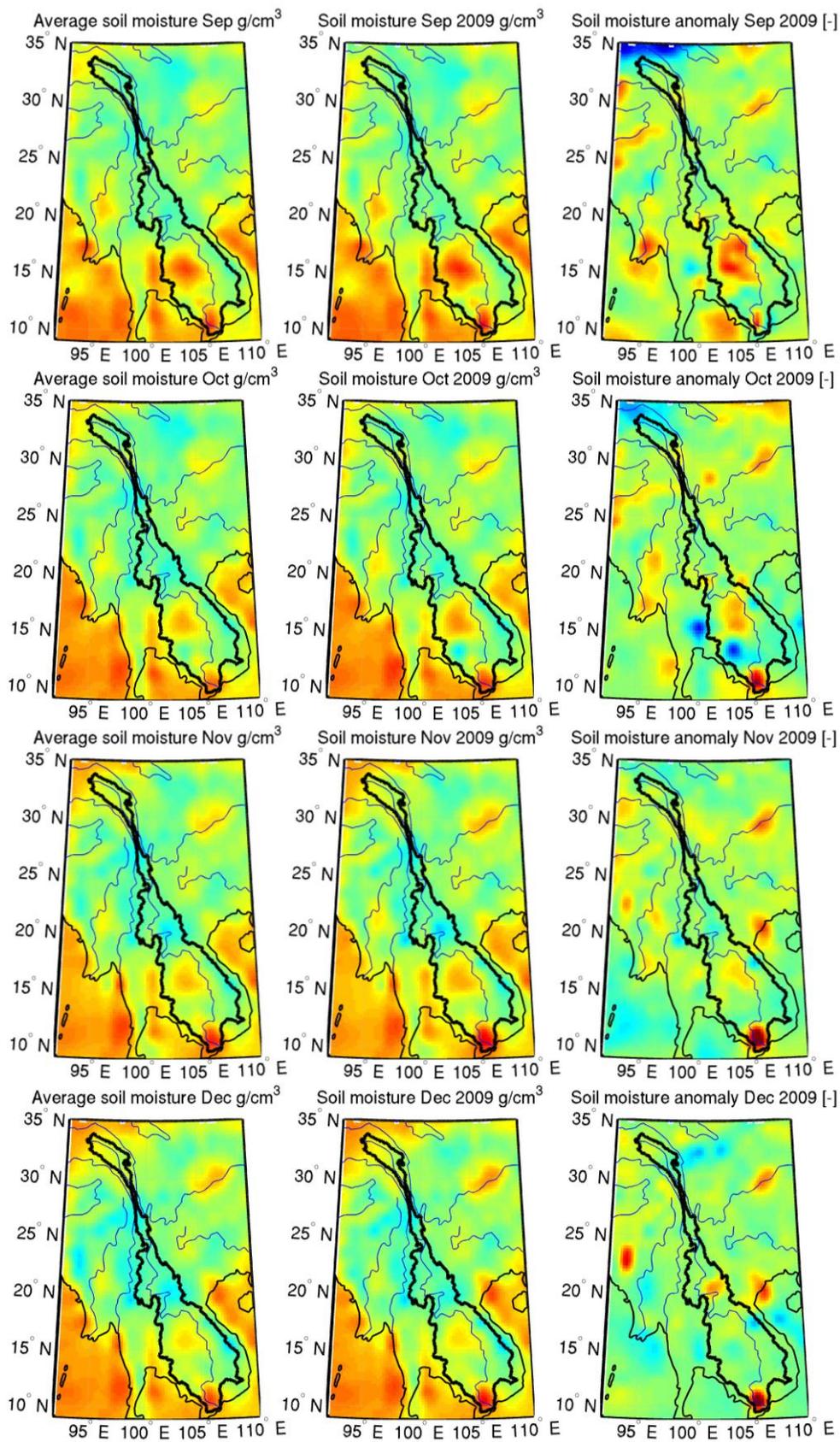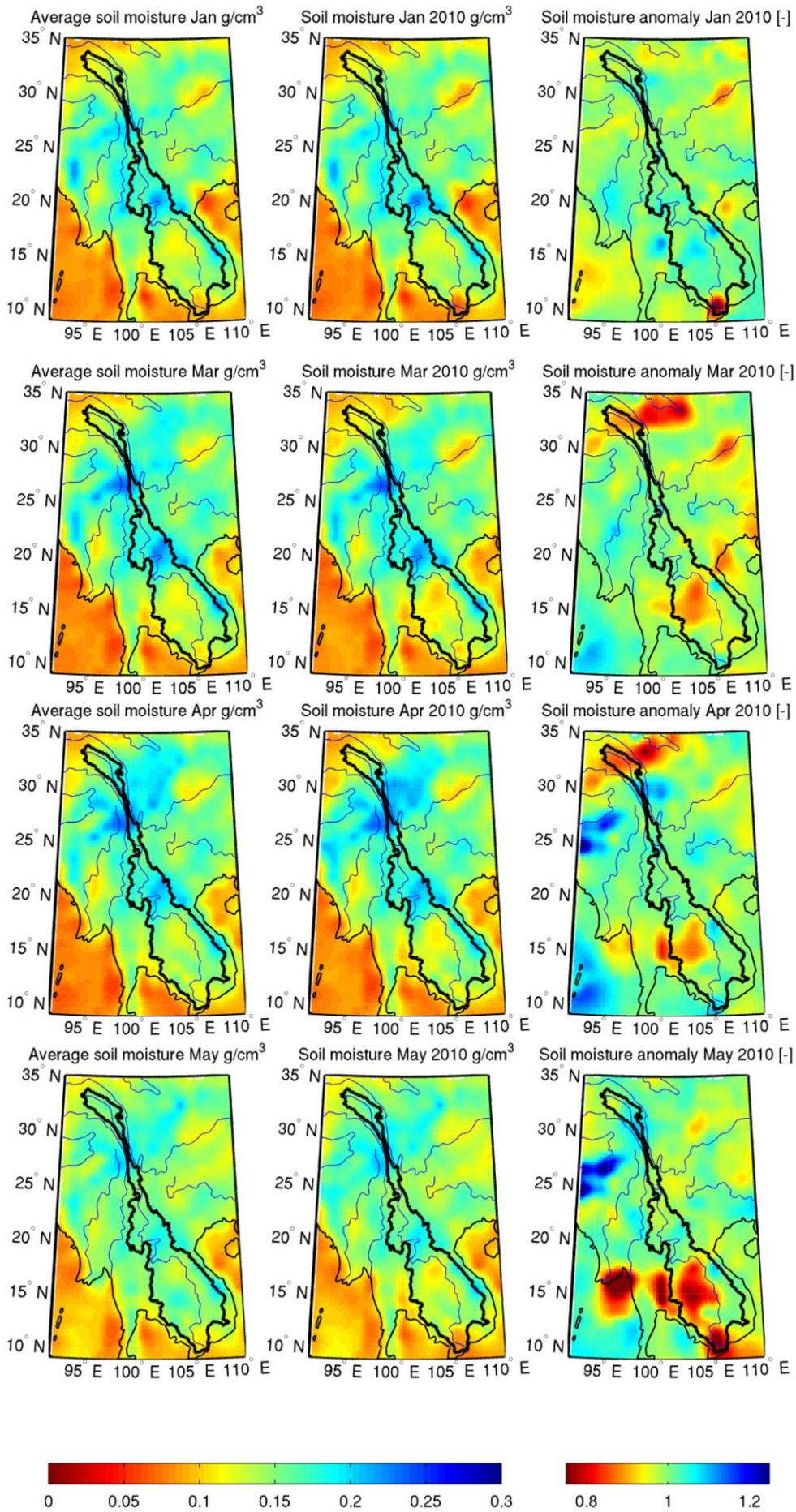Average NDVI Mar   NDVI Mar 2010   NDVI anomaly Mar 2010
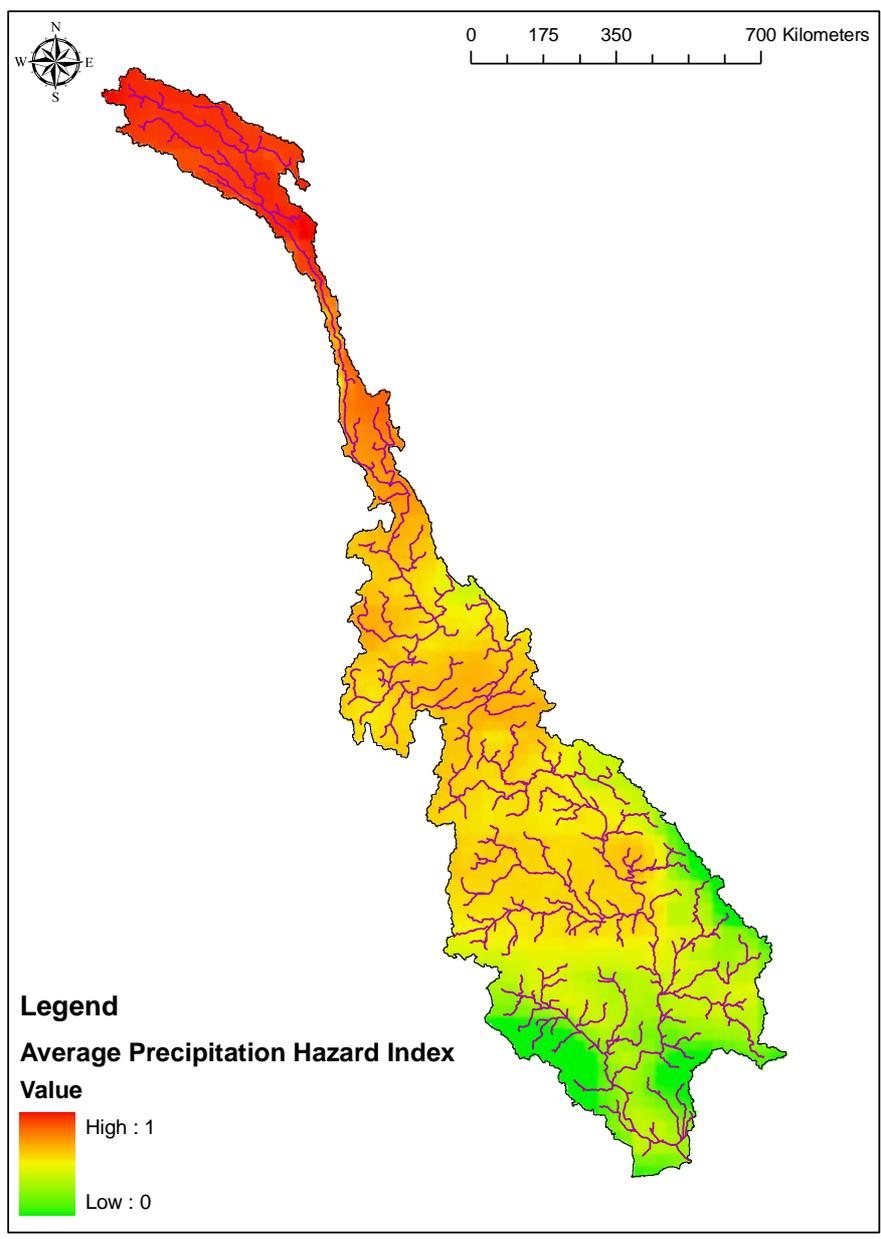
Average NDVI May   NDVI May 2010   NDVI anomaly May 2010
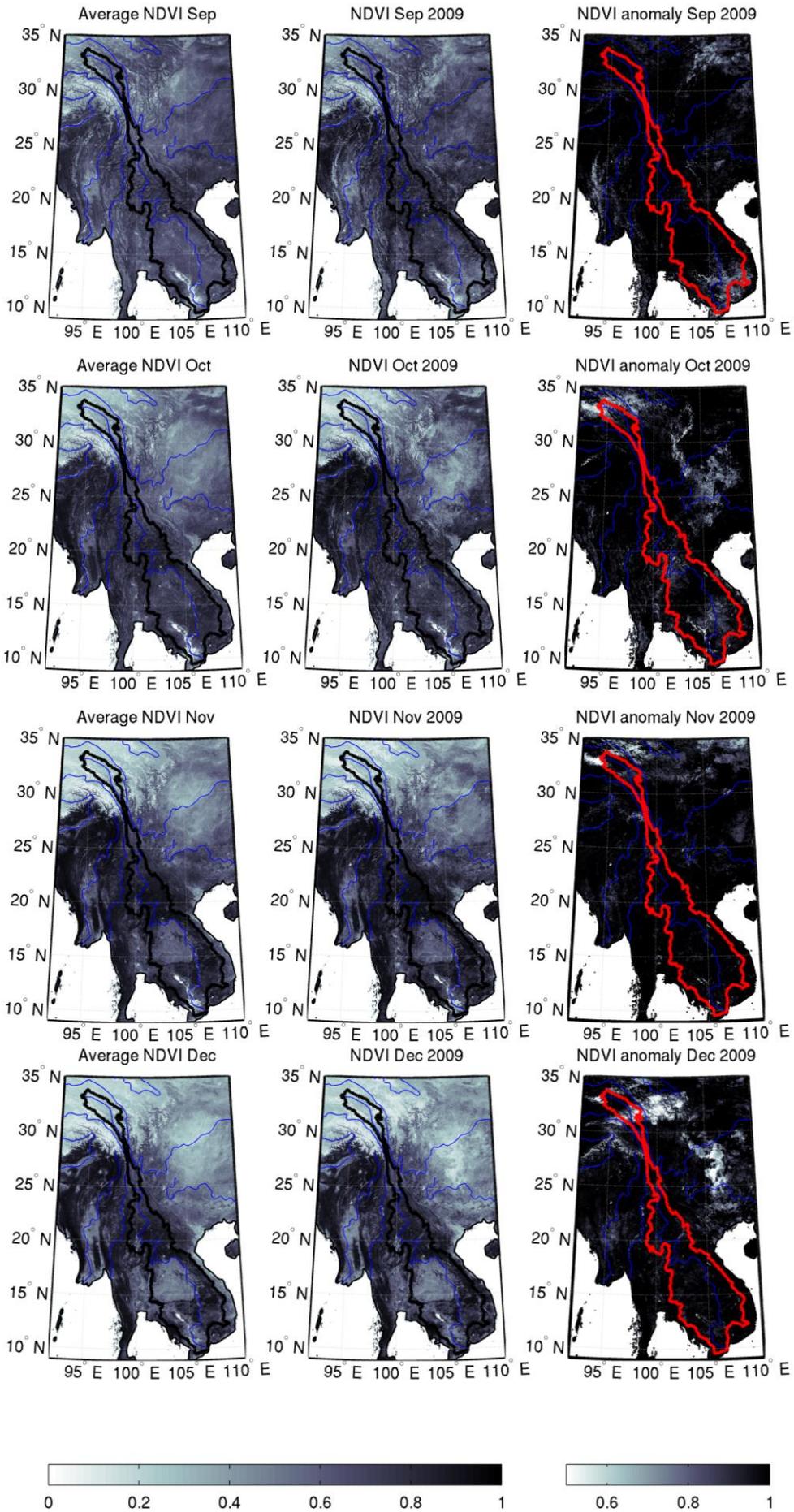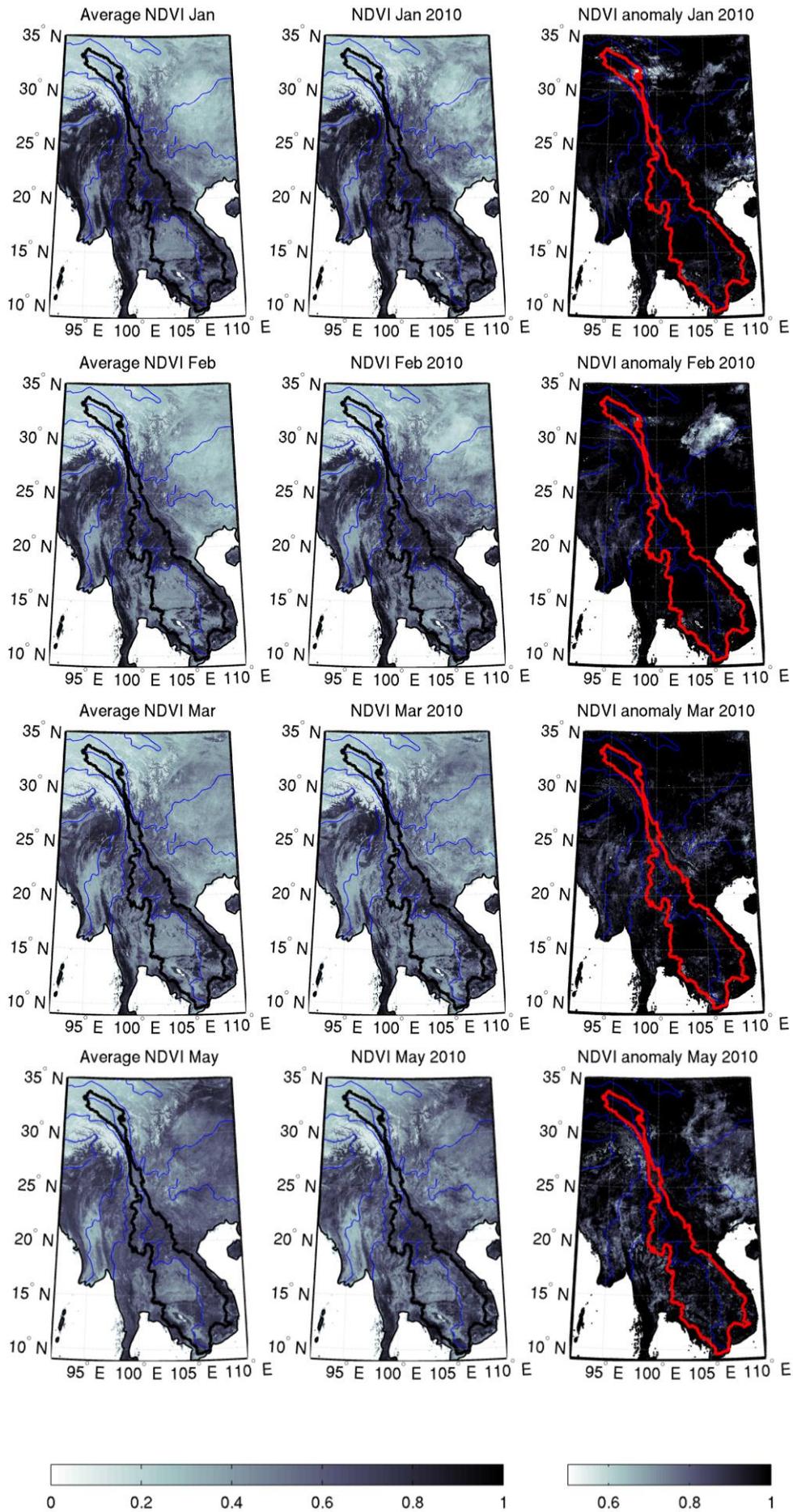
Appendix 5: Soil moisture maps

Appendix 6: Hazard Index maps

Legend

Average Precipitation Hazard Index

Value

High : 1

Low : 0

Legend

CV precipitation Hazard Index

Value

High : 1

Low : 0

Legend

Average NDVI Hazard Index

Value

High : 1

Low : 0

0   175   350   700 Kilometers

Legend

CV NDVI Hazard Index

Value

High : 1

Low : 0

Appendix 7: Vulnerability Index maps

Legend

Population Vulnerability Index

Value

High : 1

Low : 0

Legend

GDP Vulnerability Index

Value

High : 1

Low : 0

Legend

Landuse Vulnerability Index

Value

High : 1

Low : 0

Legend

Distance to river Vulnerability Index

Value

High : 1

Low : 0