Mekong River Commission
For Sustainable Development

ANNUAL MEKONG FLOOD REPORT 2017

Aspects of hydrology and extreme weather phenomena in flood and drought forecasting in the Lower Mekong Basin (LMB)

September 2019

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The main observation stations along the mainstream of the Mekong River in the Lower Mekong Basin.

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List of Abbreviations

ADB	Asian Development Bank
AHS	Automatic Hydrological Station
AMFR	Annual Mekong Flood Report
AWS	Automatic Weather Station
CCDM	Commune Committee for Disaster Management
CCI	Climate Change Initiative
CDI	Combined Drought Index
CDNDPAC	Central Department of Natural Disaster Prevention and Control
CNMC	Cambodia National Mekong Committee
CRBMF	Core River Basin Management Function
CRC	Cambodian Red Cross
CSCNDPC	Central Steering Committee for Natural Disaster Prevention and Control
DAHITI	Database for Hydrological Time Series of Inland Waters
DCC	Department of Climate Change
DDPM	Department of Disaster Prevention and Mitigation
DEM	Digital Elevation Model
DHRW	Department of Hydrology and River Works
DMH	Department of Meteorology and Hydrology
DMS	Drought Management Strategy
DOM	Department of Meteorology
DRR	Disaster Risk Reduction
DWR	Department of Water Resources
EAWM	East Asia Winter Monsoon
EASM	East Asia Summer Monsoon
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Nino Southern Oscillation
EPP	Emergency Preparedness Plan
ESA	European Space Association
ESCAP	Education and Science Centre for Asia and the Pacific
EWS	Early Warning System
FEWS	Flood Early Warning System
FMMP	Flood Management and Mitigation Program
GDAL	Geospatial Data Abstraction Library
GDNDPAC	General Department of Natural Disaster Prevention and Control
GDP	Gross Domestic Product
GFAS	Global Flood Alert System

GISTDA	Geo-informatics and Space Technology Development Agency
GMS	Greater Mekong Sub-Region
GPCC	Global Precipitation Climatology Centre
HM	Hydrological and Hydraulic Modelling
HYCOS	Hydrological Cycle Observing System
IHFE	International hydrology/flood expert
ITCZ	Inter-Tropical Convergence Zones
LMB	Lower Mekong Basin
LNMC	Lao National Mekong Committee
MAFF	Ministry of Agriculture, Forestry and Fisheries
MCs	Member Countries
MFW	MODIS Flood Water
MODIS	Moderate-resolution Imaging Spectroradiometer
MOEYS	Ministry of Education, Youth and Sports
MOH	Ministry of Health
MOP	Ministry of Planning
MOWRAM	Ministry of Water Resources and Meteorology
MRC	Mekong River Commission
MRCS	Mekong River Commission Secretariat
NASA	National Aeronautics and Space Administration
NCDM	National Committee for Disaster Management
NDCE	National data collection experts
NDMO	National Disaster Management Office
NDVI	Normalized Differenced Vegetation Index
NDWI	Normalized Differenced Water Index
NECC	National Emergency Committee Centre
NFFC	National Flood Forecasting Centre
NHFE	National hydrology/flood experts
NHMFC	National Centre of Hydrology and Meteorology Forecasting
NMC	National Mekong Committee
NOAA	National Oceanic and Atmospheric Administration
NWFPC	National Water Resources and Flood Policy Committee
NWP	Numerical Weather Prediction
PCDM	Provincial Committee for Disaster Management
PDOWRAM	Provincial Department of Water Resources and Meteorology
PHSI	Palmer Hydrologic Drought Index
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation

RFDMC	Regional Flood and Drought Management Centre
RFMMC	Regional Flood Management and Mitigation Centre
RFSS	River Flood Forecasting System
RID	Royal Irrigation Department
SDI	Streamflow Drought Index
SDNDPAC	Southern Department of Natural Disaster Prevention and Control
SPEI	Standardised Precipitation-Evapotranspiration Index
SPI	Standardized Precipitation Index
SRE	Satellite Rainfall Estimates
TMD	Thai Meteorological Department
TS	Tropical Storm
TY	Typhoon
UAV	Unmanned Aerial Vehicle
UNDP	United Nation Development Programme
URBS	Unified River Basin Simulator
VCI	Vegetation Condition Index
VDMT	Village Disaster Management Team
VNMC	Viet Nam Mekong Committee
WMO	World Meteorological Organisation

1 SYNOPSIS

This document is the 13th in a sequence of Annual Mekong Flood Reports (AMFR) by the Mekong River Commission (MRC). From the hydrological viewpoint, the year 2017 was rather normal without exceptionally big floods or devastating drought periods. But 2017 is special in so far as it is the last report in the Annual Mekong Flood Report format.

In 2019, the Mekong River Commission announced a new effort to address flood and drought issues in the Mekong region. During its bi-annual meeting, held in Viet Nam's Vung Tau City, the Joint Committee as the governing body of the MRC decided to integrate drought monitoring and management functions into the Regional Flood Management and Mitigation Centre (RFMMC) and to change the name of the centre to the Regional Flood and Drought Management Centre (RFDMC). The new RFDMC will remain in Phnom Penh where its predecessor successfully operated for years.

The tasks of the new centre comprise flood and drought forecasting. According to the Chairperson of the Joint Committee for 2019, Dr Le Duc Trung, the decision was made to address the changing context of the basin and its vulnerability to more extreme weather events due to climate change, and to be more agile and responsive.

With the move towards a more integrative approach, the report has been renamed as the Annual Mekong Hydrology Report (AMHR). The new format will be employed in 2018.

This AMFR has the theme "Aspects of hydrology and extreme weather phenomena in flood and drought forecasting in the LMB". Although still dominated by floods, this report also addresses drought issues and paves the way for its transition to a hydrology report.

This report elaborates on methods to assess conditions in the LMB, tools for forecasting flood and drought, and explains the regional flood and drought situation in the current year by means of one overarching and four country-related sections.

With the new format in mind, this last AMFR 2017 was expanded to some extent towards drought, raising the topics of meteorological, hydrological, agricultural, and socio-economic drought. However, what will remain a task for the future is the coverage of drought impacts. If impacts due to drought are to be addressed in the future, socio-economic drought is relevant and requires the identification of water deficits and knowledge of water demand. This opens up a new field, which has never before been tackled in the annual report series.

In recent years, the Mekong River basin has experienced remarkable alterations. One of the most striking and controversially discussed features is the development of water infrastructure. Large dams affecting the hydrological regime, ecology, and socio-economy in an unprecedented way, are planned and being built in the tributaries and along the Mekong mainstream. As such, the AMHR format, with its broader perspective, is equipped to cope with the new challenges.

2 ASPECTS OF HYDROLOGY AND EXTREME WEATHER PHENOMENA IN FLOOD AND DROUGHT FORECASTING IN THE LMB

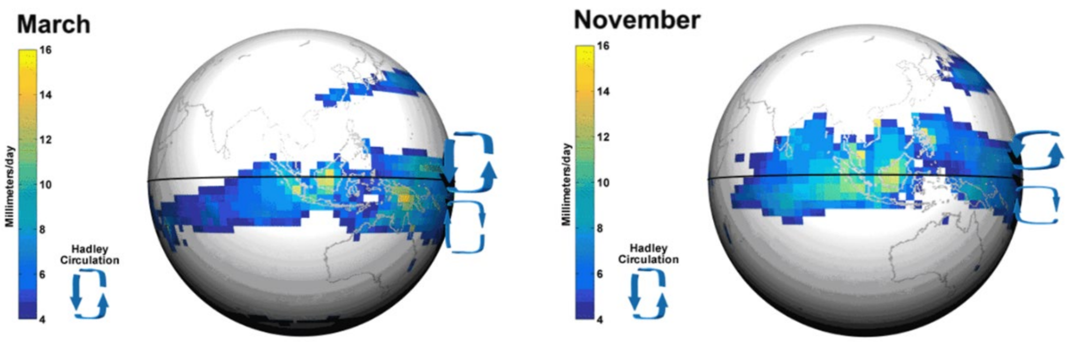
2.1 Excess Water

2.1.1 The Monsoon

Monsoon is the main driver for extreme weather phenomena in Southeast Asia. The word monsoon stems from the Arabic word "mausim", which means season. Seasonality of weather is caused by the earth's inclination. Warming and cooling of the northern and southern hemisphere depends on the earth's position to the sun and the different land masses mainly influencing the regimes of the monsoon. Southeast Asia is affected by two monsoon regimes: the Southeast Asian summer monsoon (10°–20°N) and the western North Pacific summer monsoon (10°–20°N, 130°–150°E). They are separated by a boundary over the South China Sea (Kripalani & Kulkarni, 1997). This seasonality is the main driver of the rain regime over the LMB.

During winter, less solar radiation in the northern hemisphere results in cooler temperatures and lower pressure in the atmosphere. This effect reaches Southeast Asia giving rise to the dry East Asia Winter Monsoon (EAWM) (Loo, Billa, & Singh, 2015). During summer, the southwest monsoon rainfall is controlled by the warming of the northern hemisphere, where the heated air rises and is transported by the monsoon wind towards the southern hemisphere (Wolfson, 2012). The East Asian summer monsoon (EASM) is the key source of water for the LMB.

These large air moves cause a pattern in the tropical atmosphere called the Hadley Circulation. Where the solar radiation is perpendicular to the Earth's surface, air warming is highest, air rises and transports water vapour in the upper atmosphere, approximately 10-15 kilometres above the Earth's surface. As it flows towards the poles, the air cools and drops down again forming two cells. The area near the equator with low pressure and converging, rising winds is called the Intertropical Convergence Zone (ITCZ).



Source: https://scied.ucar.edu/docs/why-monsoons-happen

Figure 1: Example of ITCZ, winds, and rain pattern change for March and November (https://scied.ucar.edu)

The EASM is dominated by the Western Pacific Subtropical High. Zhou, Yu, Zhang, Drange, and Cassou (2009) and SOEST University of Hawai (2013) stated that the change in atmosphere temperature partly affects the Western Pacific Subtropical High, which directly influences the EASM and in turn, can provide a source of climate predictability of the EASM.

Researchers have found some large scale and long-lasting changes to the monsoon system. Zhou, Yu, Zhang, Drange, and Cassou (2009) observed a westward shift of the Western Pacific Subtropical High since the late 1970s due to the atmospheric response of the Indian Ocean – Western Pacific warming. Schewe and Levermann (2012) predicted that increasing temperatures in the late 21st century and early 22nd century will cause frequent changes and shifts to monsoon precipitation up to 70% below normal levels. In addition, many studies link monsoon variability with the El Niño Southern Oscillation (ENSO) but this is confined to its year-to-year variability.

2.1.2 Events of extreme rainfall

While large-scale atmospheric regimes bring forth general weather conditions like the monsoon, extreme rainfall events are attributable to smaller scale events like monsoon depression convection or cyclones.

Analysing rainfall events requires the distinguishing of rainfall Intensity, Duration and Frequency. These IDF curves show in a concise way the characteristics of rainfall for a particular point or area. IDF curves provide recurrence intervals and associated rainfall in mm. IDF curves are usually used to derive design storms from which hydrographs are derived by using hydrological models. The resulting hydrographs are then used to design dam spillways, to check vulnerability to floods, to design flood protection measures, and to design culverts, etc. This is a standard approach for flood mitigation measures.

Apart from rainfall intensity and duration, antecedent moisture conditions, river water levels prior to an event, location of settlements, early warning procedures, and preparedness and resilience are factors that greatly influence impacts from extreme rainfall. Table 1 gives an exemplary excerpt of flooding that occurred within the LMB. As can be seen, the links between the amount of rainfall and respective impacts vary, making the need for a holistic approach of the flooding and impact chain necessary (e.g. through modelling) to predict the effects of flooding.

Table 1: Selected extreme rainfall events and their impacts

Year	Country	Event	Flood description	Impact
2005	Lao PDR	two times 200mm daily precipitation in Thakek 45-550mm from end of July to September	13m flood stage at Thakek flash floods in central/southern region	> 480,000 people affected > 2000 livestock lost 560km^2 paddy fields lost
2007	Cambodia	more than 200mm precipitation in two days	flood peak of 14m at Sre Pok at Lumphat	160,000 people affected, 80 km^2 of crops lost
2009	Vietnam	more than 500mm precipitation in three days in central region	historical maximum inundation and flash flooding	163 people killed, 575,000 houses impacted, 1060 km^2 crops damaged
2014	Thailand	80-115mm in three days in northern part of country	flooding in 10 provinces	1916 villages and 207,000 people affected

Maximum observed daily rainfall at most stations in the LMB range between 125 to 250 mm. Some locations have experienced values with more than 500 mm in a day. Rainfall amounts over 400 mm are more common along Vietnam coastal stations. Daily maximum precipitation taken from 169 ground stations in the LMB between 2006 and 2017 is given in Figure 2. Whether all records are absolutely reliable is difficult to say; however, daily rainfall with more than 400 mm is not uncommon and is mentioned in (US Corps of Engineers, 1970).

A relevant factor in analysing rain is the deviation of isohyetal maps. US Corps of Engineers (1970) evaluated different tropical storm and cyclone events and found rainfall depths of more than 350 mm in 24 hours over an area of 1000 km^2 during the storm Tilda from September 21 to 25, 1964. Even an area of 100 000 km^2 experienced an average of 120 mm in 24 hours. Isoheytal maps are also given in MRC (2014).

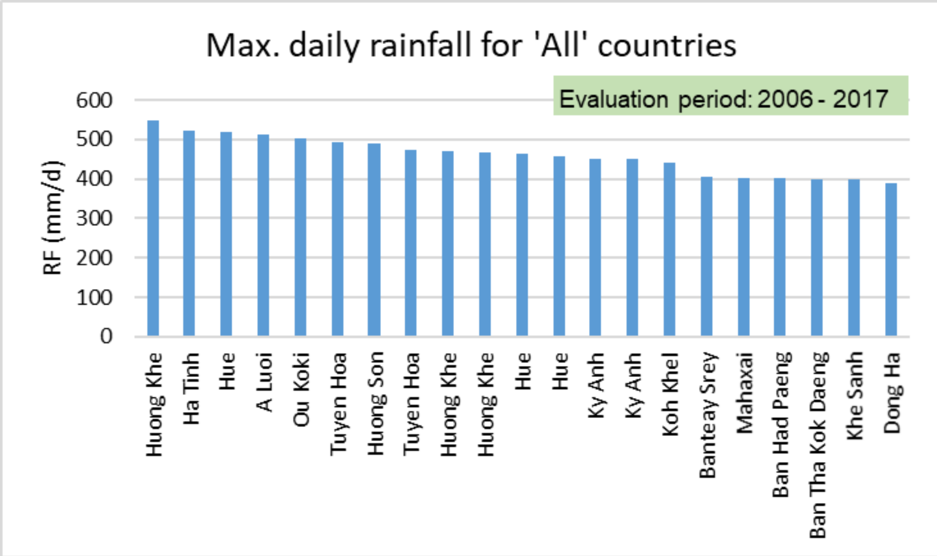


Figure 2: Maximum daily precipitation from 169 observation stations between 2006 and 2017 (source: MRC data repository)

When extreme rainfall with high intensity persists for days and areal mean rainfall is high (e.g. in the wake of cyclone events) resulting flooding can be disastrous for large areas, especially when it coincides with adverse drainage conditions as happened in 2011 in Thailand.

Figure 3: Flood impact in (a) Lao PDR 2005, (b) Cambodia 2007, (c) Vietnam 2009 (d) Thailand 2014 (pictures taken from the respective AMFRs)

2.2 Water shortages

2.2.1 Types of droughts

Generally, droughts are divided into four categories: meteorological, hydrological, agricultural, and socio-economic (Figure 4). They differ with respect to their nature and effects. The recognition of drought conditions starts with the anomaly of below average rainfall. The difficulty in dealing with droughts is their gradual onset. There is no clear definition about the onset of a drought. When, how, and to what extent counter-measures start is largely ambiguous and depends on the perception of decision makers. If drought conditions occurred in the past, the rain-fed agriculture-based rural economy in the region of the LMB was the most vulnerable sector.

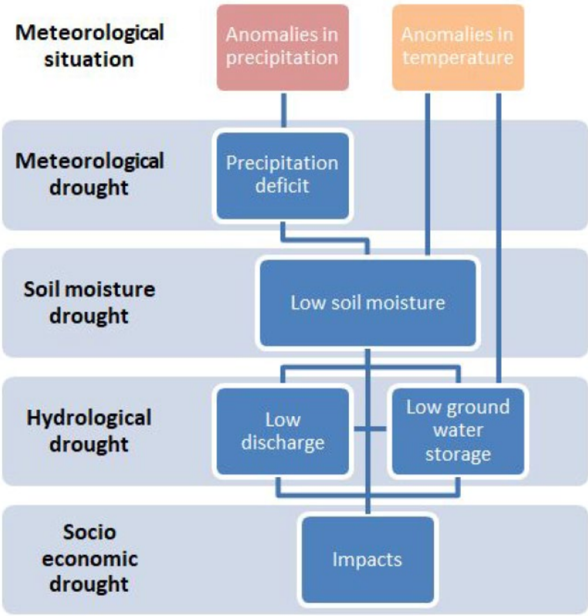


Figure 4: Types of drought and how they develop based on natural conditions (Felipe, Muñoz, Hour, & Kiem, 2018) cited from Van Loon (2015)

Drought indices are used to define when and where a drought occurs. However, to recommend a suitable drought index, the definition of the respective drought must be clear. More than 100 definitions of a drought were defined 35 years ago and were classified into four groups (Wilhite & Glantz, 1985): meteorological, hydrological, agricultural, and socio-economic. For these different groups, different drought indices exist (Figure 5). Hence, before selecting a suitable index, the decision must be made concerning which drought definition is of interest. Good overviews are available in WMO and GWP (2016).

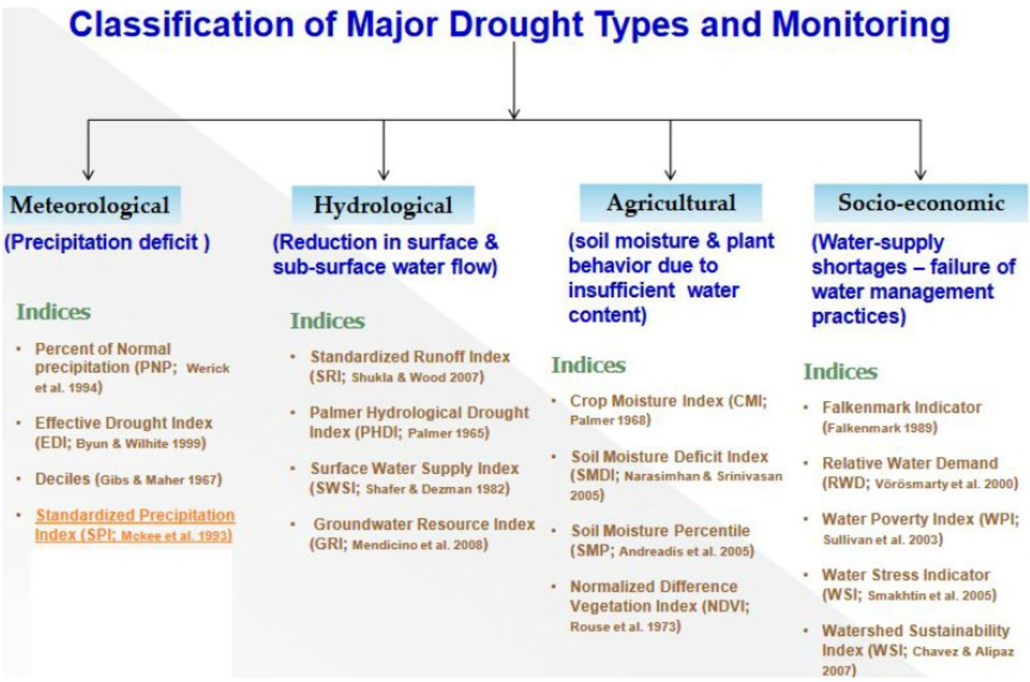


Figure 5: Drought types and most widely used indices for classification (Felipe, Muñoz, Hour, & Kiem, 2018) cited from Ganguli (2013)

Meteorological drought is defined as a dry period with below average precipitation and/or above average potential evapotranspiration. It is usually the first and immediately recognizable drought. The Standardized Precipitation Index (SPI) is the most common and basic index to define meteorological droughts. It is widely applied due to its simplicity and low data requirements. It only requires precipitation as input and can be calculated taking different numbers of months as accumulation periods into consideration. Extending the SPI with evaporation leads to the SPEI (the Standardised Precipitation-Evapotranspiration Index), which has the advantage of also considering the impact of mainly temperature on the drought conditions. The SPEI is for instance available from the SPEI Global Drought Monitor for the whole globe on a monthly time step in a 1-degree (about 100km at the equator) resolution (http://spei.csic.es). It utilizes precipitation data from the GPCC (Global Precipitation Climatology Centre) and temperature data from NOAA (National Oceanic and Atmospheric Administration) to estimate potential evapotranspiration with the Thornthwaite method. While the globally available SPEI can give a quick overview of the general conditions (Figure 6), it may be too coarse to assess regional drought conditions (e.g. for agricultural decisions and management). For those, calculations of the SPEI based on high-resolution station-based or satellite-based data is more suitable.

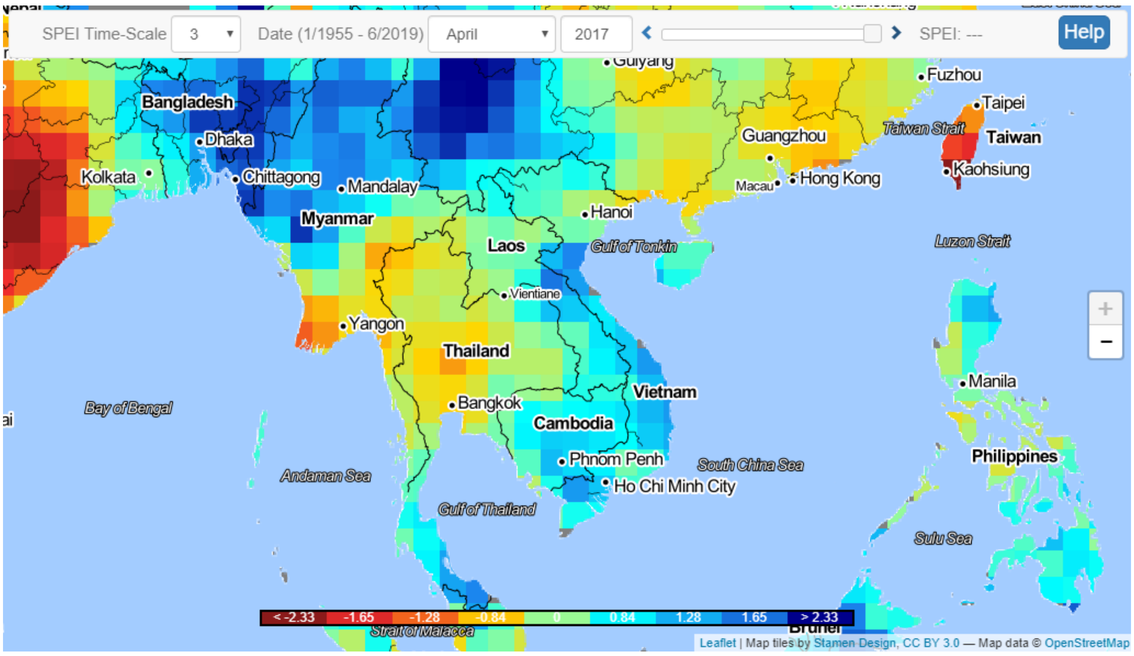


Figure 6: SPEI from the Global Drought Monitor for April 2017, showing no significant drought conditions in the LMB, with slightly dry conditions in Thailand

Hydrological drought is defined as a period in which drought conditions lead to low water availability in rivers, streams, groundwater, or other water bodies. Hydrological drought usually lags meteorological drought by a certain time period, depending on the latency of the basin. Typical indices to characterise hydrological drought are the SDI (Streamflow Drought Index) or the PHSI (Palmer Hydrologic Drought Index). The SDI is largely based on the calculation methods of the SPI using monthly streamflow data instead of precipitation. The PHSI integrates meteorological data with soil properties to assess longer-term dryness, which will affect water resources.

Agricultural drought is defined as a situation in which meteorological and/or hydrological drought leads to conditions that impact agricultural plant development negatively. Agricultural droughts are more complex to define and assess since they depend on the type of crop currently planted and also on the life stage, time of the growing season, and rooting depth of the plants. Agricultural drought can be assessed via remote sensing, e.g. through the Vegetation Condition Index (VCI), which is based on the NDVI and compares current vegetation status to previous historical conditions.

These indexes are based on physical data that is measured/observed and hence, the indices are calculated in a straightforward manner. The advantage of these indices is that through short-term weather or seasonal climate forecasts, they can be used to predict when a drought may occur in the near or medium-term future.

Socio-economic drought is the most complex definition of a drought. It is defined as a situation in which one of the previously defined droughts may lead to impacts on the economic and social system. It is also the most difficult to calculate and to predict since it includes the physical water availability on one hand and the required water demand on the other hand, including an estimate on the consequences. This can be obtained from detailed observations and statistics but may also be based on the application of models.

A common attribute to all drought indices is the aggregation period. In monsoon influenced regions, 3-month aggregation is considered suitable for meteorological indices like the SPI according to Svoboda, et al. (2012). However, a three-month period might be too short when taking agricultural and other sectors into account.

Apart from rain-fed agriculture, severe drought conditions with various effects occur in the LMB if the rainy season is weak and the flood water level in the Mekong mainstream remains low. The consequences are manifold depending on location:

- Low flow conditions at the confluence with the outflow of the Tonle Sap reduce reverse flow to Tonle Sap preventing the lake from inundating adjacent plains with adverse consequences for agriculture, fish production, and ecology.
- Low flow volumes discharging into the Mekong Delta favour saltwater intrusion in the Mekong Delta affecting soil quality and thus agricultural productivity.

2.2.2 Drought events in the LMB

Major basin wide drought events occurred in 1992, 1997, 1998, 2002, and 2004-05, followed by more locally confined dry spells in 2015 and 2016. It is estimated that the 2004-05 drought has led to losses of at least 45 million USD in the Mekong Delta region alone (Felipe, Muñoz, Hour, & Kiem, 2018). Impacts of the other events are not systematically reported apart from a more general assessment (Felipe, Muñoz, Hour, & Kiem, 2018): during a drought year, the loss of rice production is estimated at about 10 million USD in Northeast Thailand (equivalent to about 78,000 tonnes). Another example is the impact on fisheries in the Tonle Sap with about 15 million USD losses annually in the case of a drought year.

In summary, the total losses under drought considering the frequency of drought events, may equal the costs of floods (MRC, 2012).

Approximately 40% of the time for Lao PDR and Thailand and ~33% of the time for Cambodia and Vietnam over the period 1950-2004 are regarded as drought conditions. This relatively high frequency of dry spells and associated costs, known for some specific locations within the LMB, suggests that the average annual cost of drought in the LMB is greater than the average annual cost of flood damage (MRC, 2012).

This calls for the development of an LMB drought monitoring and forecasting system. The serious socioeconomic impacts of the recent 2014-2015 drought that occurred across the LMB further emphasises the need for a reliable LMB drought monitoring and forecasting system.

Therefore, the MRC (2019) has embarked on assessing droughts to:

- Review all drought indices (nowcasts and forecasts) available from the Asian Disaster Preparedness Centre (ADPC) via the United States National Aeronautics and Space Administration (NASA) and SERVIR-Mekong Regional Hydrologic Extreme Assessment System (RHEAS).
- Develop an easy to understand, informative website to communicate current and forecast LMB drought conditions to Member Countries and other stakeholders. The website should be based on the drought indices (nowcasts and forecasts) from RHEAS that are provided by ADPC.
- Develop a template for MRC to provide annual drought monitoring and forecasting reports.

More information can be found here: http://droughtforecast.mrcmekong.org/maps

The system is operational and provides methodologies for nowcast and forecast based on meteorological, agricultural, and hydrological droughts indices.

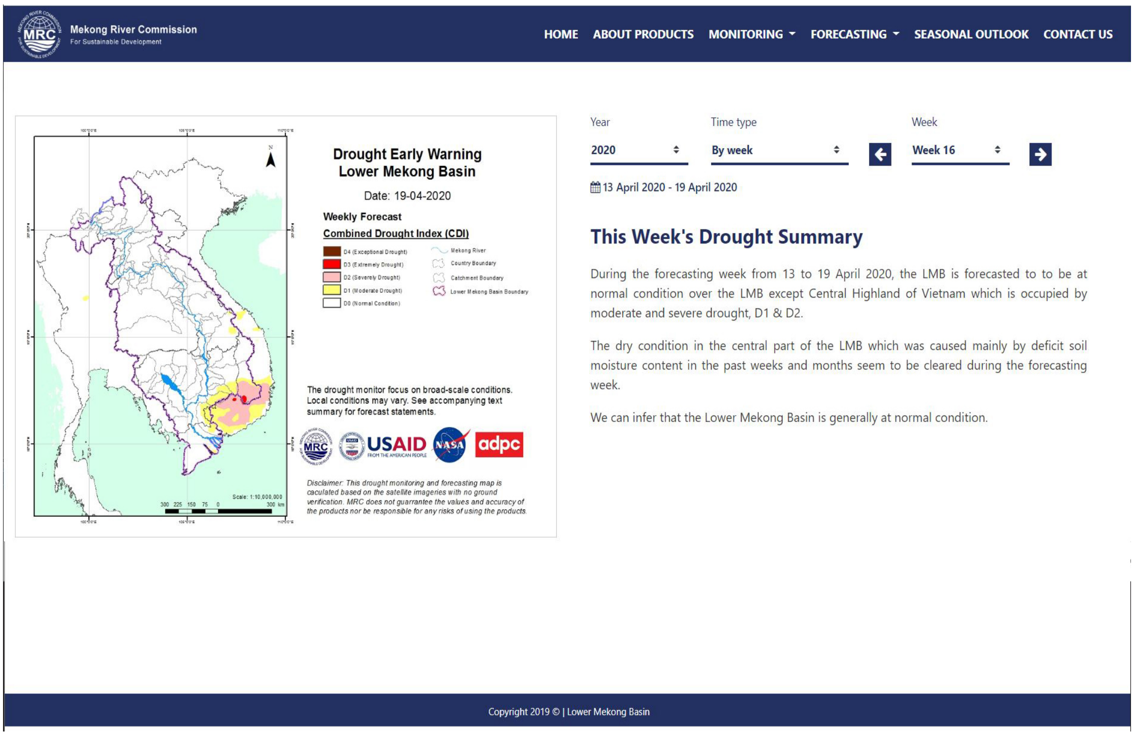


Figure 7: The MRC Drought Monitoring and Forecasting website (http://droughtforecast.mrcmekong.org/maps)

2.3 Methods to assess recent and actual conditions

Suitable approaches to monitor and assess flood and drought conditions in the LMB can generally be distinguished into remote-sensing and ground-based assessments. Remote sensing techniques are intended to complement the existing monitoring network in both space and time. In the following subchapters, remote sensing of floods, soil moisture, water levels in water bodies and index-based assessments are described and analysis is given for 2017 conditions in the LMB. This is complemented by describing the current MRC monitoring network.

2.3.1 Flood mapping

Flood mapping using remote-sensing data provides useful information for assessing the spatial flooding conditions and for characterising the 2017 flood conditions in comparison to the long-term historical situation.

The Moderate-resolution Imaging Spectroradiometer (MODIS) instrument has been orbiting the earth in two satellites since 1998 and 2002. The instruments provide data in 36 spectral bands and map the entire earth surface every two days (https://modis.gsfc.nasa.gov/data/). Besides other usages, it can also depict water surfaces which are further processed by NASA to the Near-Real-Time Global Flood Mapping product (https://floodmap.modaps.eosdis.nasa.gov). These maps, currently still flagged as experimental, have a 250m resolution and have been available on a three-day time step from 2003 onwards.

The product is available with a latency of one – two days making it useful for near real-time disaster response. Further advantages of the dataset are, that it can cover vast areas with a similar approach and accuracy over the whole basin and is therefore comparable. It is available free of charge and relatively simple to process (e.g. compared to hydraulic flood mapping) and includes both inundation from riverine flooding as well as pluvial flooding as long as it is visible within a 250m resolution. Disadvantages are that inundation under dense vegetation and cloud cover is not visible and that a distinction between riverine flooding and pluvial flooding is not possible.

Raw inundation data can be downloaded after registration in different formats and time steps. For the AMFR 2017, all available data from January 2010 onwards was downloaded as GeoTiff in 3-day composite time steps for the longitudes 100-110E and latitudes 10-20N. The dataset used is the MODIS Water Product (MWP) which shows a pixel value of 3 for areas that are inundated by flood waters in the 3-day period. The data was further processed using Python and the GDAL and xarray libraries in order to derive suitable statistics for the year 2017. Therefore, the GeoTiff files were converted to a continuous NetCDF file showing the maximum flood extent of the current month. The resulting NetCDF-file was then further processed in order to obtain the long-term (2006-2016) annual and monthly maximum flood extent as well as the annual and monthly inundation in 2017. A comparison can then be made by relating the 2017 flood extent to the historical maximum flood extent.

Figure 8 shows the flood extent in 2017 (red) in comparison to the maximum flood extent observed by MODIS between 2006-2016 (black). Considerable flooding occurred in 2017, but not as severe as during the previous decade. Especially in the upstream regions of the LMB near Vientiane, southern Thailand, and Northern Cambodia (upstream Tonle Sap), flooding was not severe. In the downstream regions near Phnom Penh and in the Mekong Delta, flooding was more extensive, but also did not reach the flood extent observed during the previous decade.

Figure 9 shows the flood extent of 2017 against the previous decade separately for each month. In the dry season months of February to April, no flooding occurs, while as expected, most significant flooding occurs in the wet season months of August to November. Flood waters recede by the end of January. The advantage of the monthly flood maps is the possibility to carry out spatio-temporal comparisons. For instance, the onset of the 2017 flood (August) was close to the maximum extent for the same month in the previous decade. However, flooding in September-November then slowed down compared to the historical maximum inundation development.

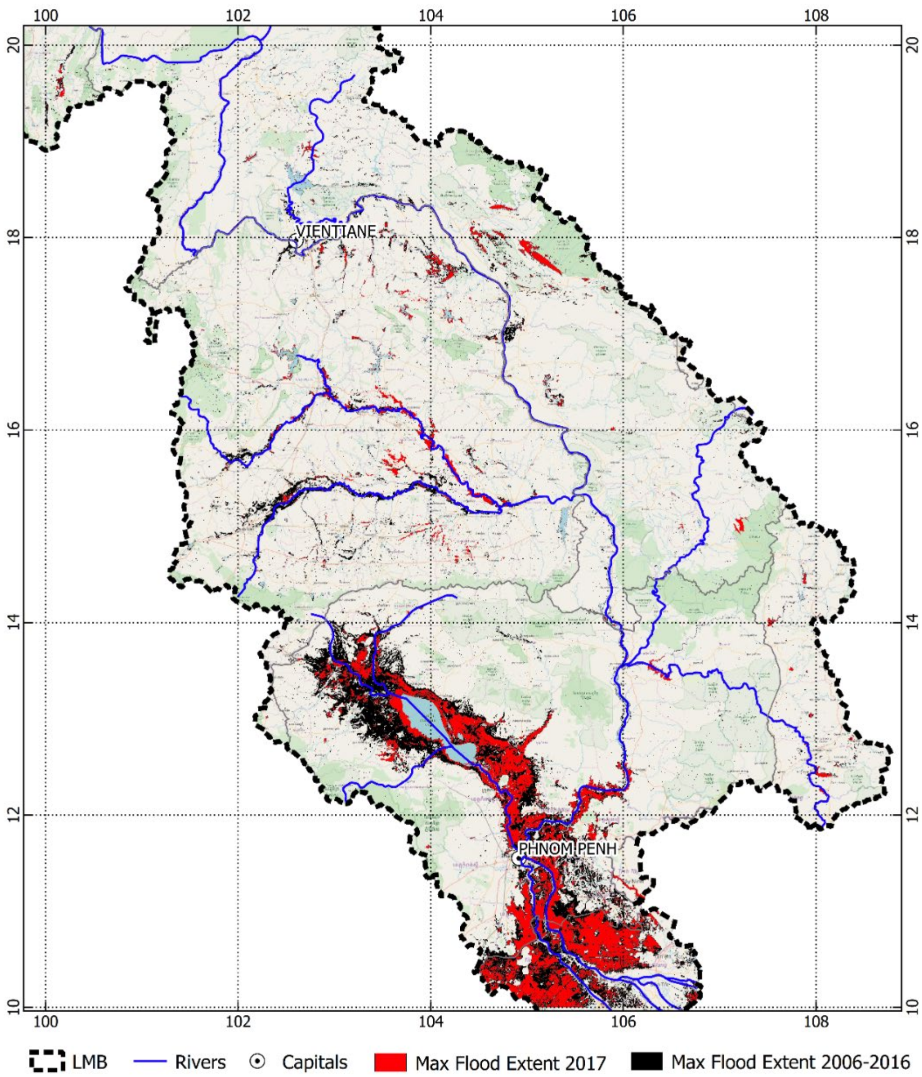


Figure 8: Comparison of maximum flooding from 2006-2016 (black) to maximum flooding in 2017 (red) in the LMB based on NASAs Near-Real-Time Global Flood Mapping (MODIS satellite) (Background image: Open Street Map)

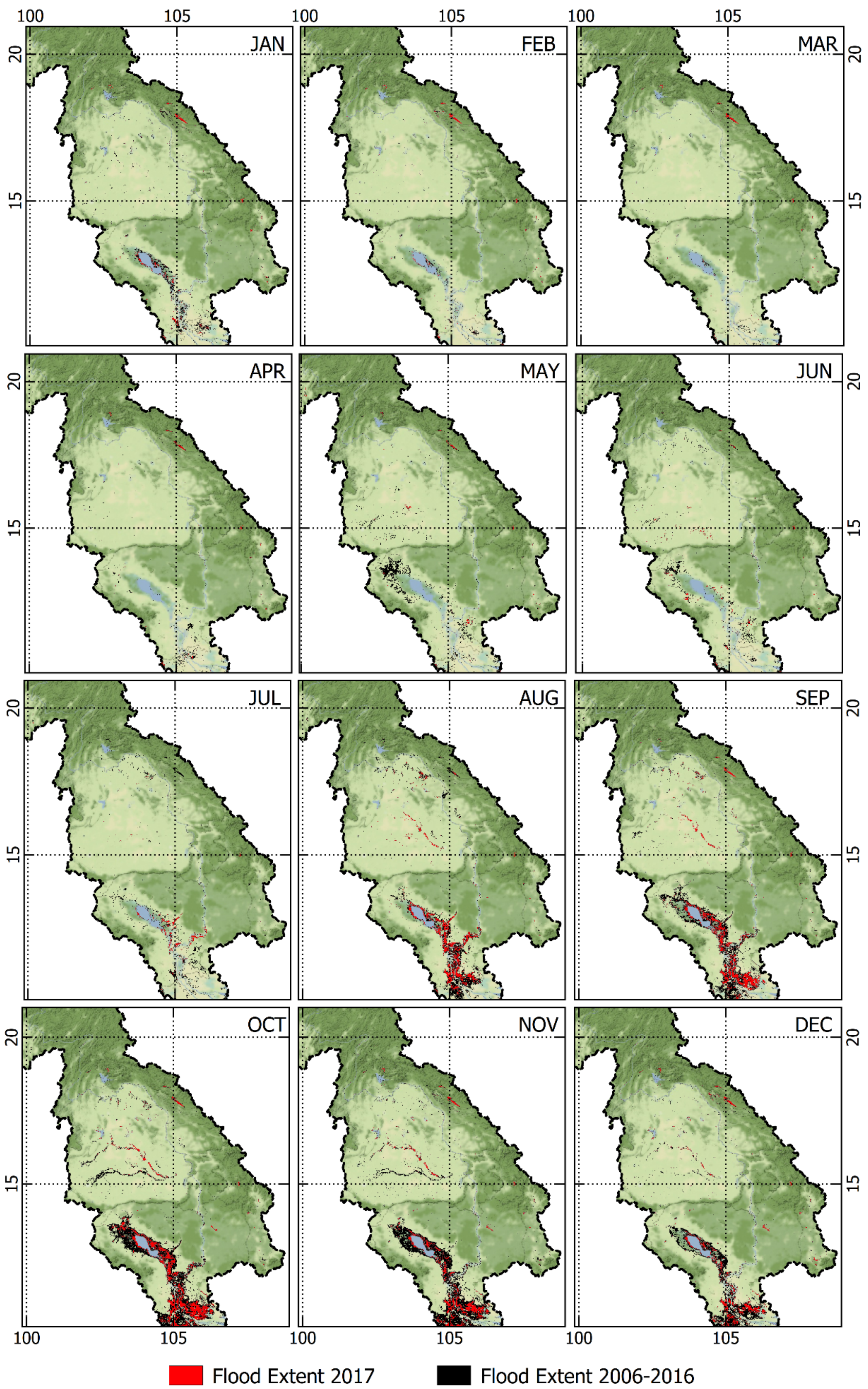


Figure 9: Comparison of maximum monthly flooding in 2006-2016 (black) to maximum flooding in 2017 (red) in the LMB based on NASAs Near-Real-Time Global Flood Mapping (MODIS satellite) (Background image: Stamen Terrain)

In essence, the MODIS dataset is a suitable product to be included in a close to near-real-time automated process in order to derive current flood extent. Furthermore, it would be possible to correlate historic flood extents with observed rainfall patterns and flow to derive a 'first guess' forecast with regards to expected possible flooding if rainfall patterns and flow were available.

2.3.2 Soil moisture

Soil moisture data from remote sensing observations provides useful information for assessing spatial drought conditions and for characterising the situation in 2017 in comparison to the long-term historical conditions. Soil moisture, for instance, is a good proxy for agricultural drought.

The most comprehensive soil moisture product today is the ESA CCI Soil Moisture (https://www.esa-soilmoisture-cci.org/), which is based on the combination of six active and passive microwave sensors. The product has been available in global NetCDF files from 1978 onwards on a daily time step in a resolution of about 25km cell size. Over the years, the data relies on nine different satellites (Figure 10) which leads to different accuracy and lower data availability for the earliest years (up to 1987).

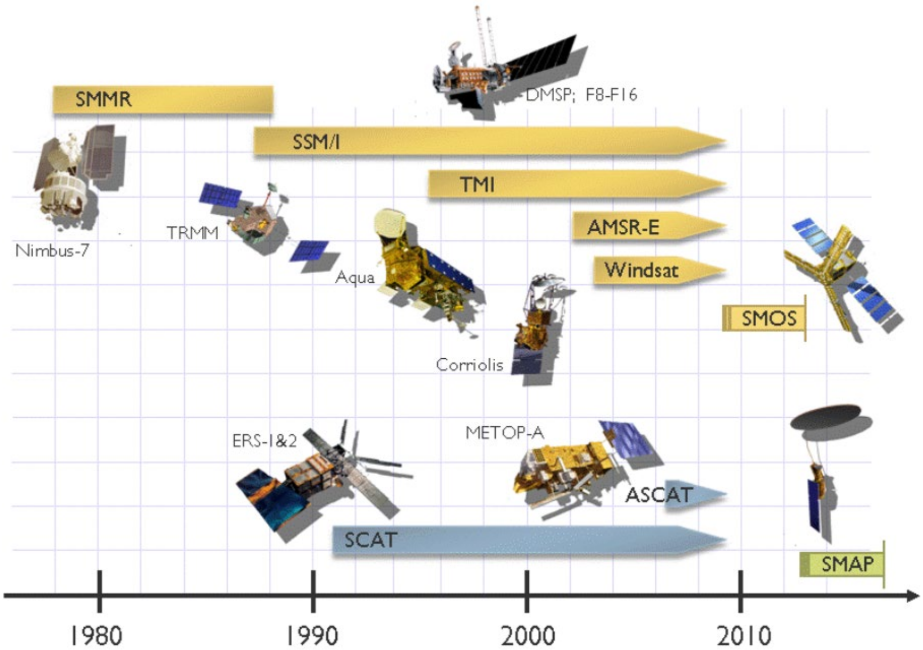


Figure 10: Satellites used over time for the ESA CCI Soil Moisture product**Error! Bookmark not defined.**

The data is processed by European research associations and updated at approximately annual periods. Currently, data is available up to June 2018. Advantages of the dataset are that it can cover vast areas, provides a similar approach and accuracy over the whole basin and is therefore comparable. Data is available free of charge and relatively simple to process. Disadvantages are the varying temporal resolution over the whole time period and lack of observations for very densely vegetated, steep mountainous, ice covered (less important form LMB), or extreme desert areas.

The soil moisture data in NetCDF format can be downloaded after registration. For the AMFR 2017, all available data from January 2006 onwards was processed and statistics were calculated using Python with the xarray library to obtain the long-term (2009-2016) annual and monthly average soil moisture per grid cell as well as annual and monthly soil moisture in 2017.

Figure 11 shows the annual distribution of soil moisture in the LMB. As can be seen from Figure 11a and b, driest regions are located more in the centre of the LMB while wetter regions are generally located towards the basin's boundaries. Figure 11c shows the percent difference in soil moisture in 2017 compared to the average soil moisture from 2006-2016. It can be seen that the LMB was, on average, wetter in 2017 than in the previous ten years (up to 40%), with a few locations north of Phnom Penh slightly drier (up to 15%).

(a) (b) (c)

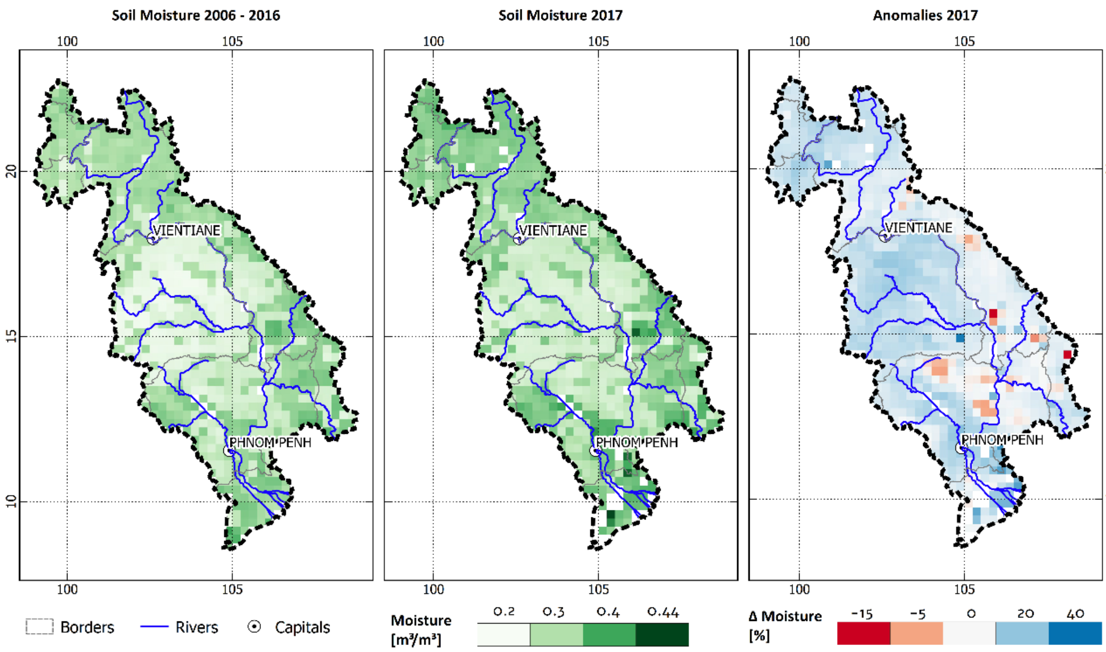


Figure 11: Comparison of (a) annual long-term average soil moisture (2006-2016); (b) soil moisture in 2017 and (c) the percent difference of 2017 compared to the long-term average in the LMB based on the ESA CCI Soil Moisture product

Figure 12 shows the monthly long-term distribution of soil moisture over the LMB. The general spatial pattern found in the annual map (Figure 11) is valid over all months, with the driest region located in the centre of the LMB. The temporal distribution shows driest conditions from December to April and wettest conditions from May to November, which matches well with the wet and dry periods in the region. The individual wet pixels in the drier centre (dark green pixels around latitude 13-17 and longitude 103-107) in the LMB are either irrigated areas or forest according to satellite images.

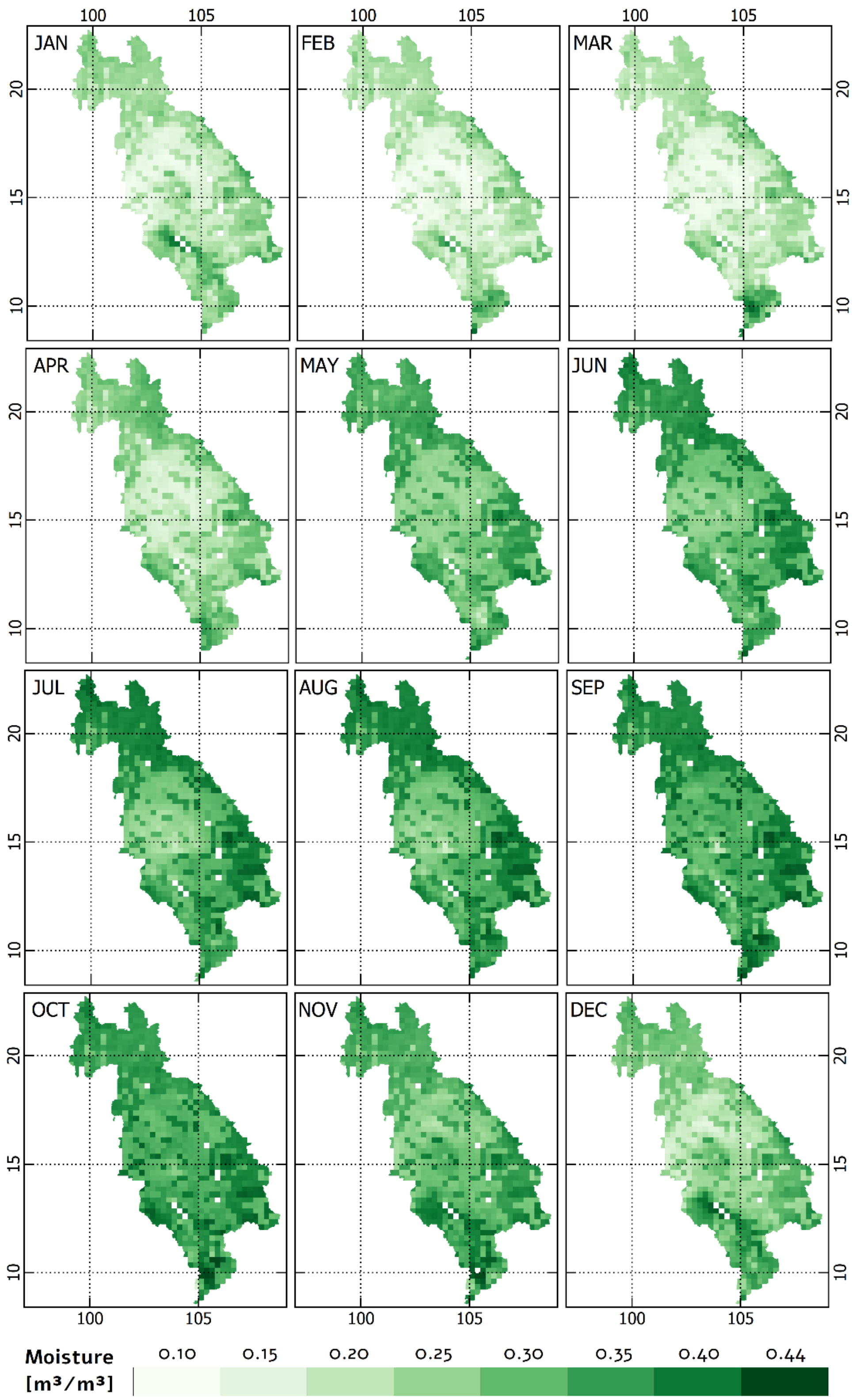


Figure 12: Monthly long-term average (2006-2016) soil moisture for the LMB based on the ESA CCI Soil Moisture product

Figure 13 shows the monthly soil moisture distribution for the year 2017, which generally follows the spatio-temporal distribution of the 10-year averages (Figure 12).

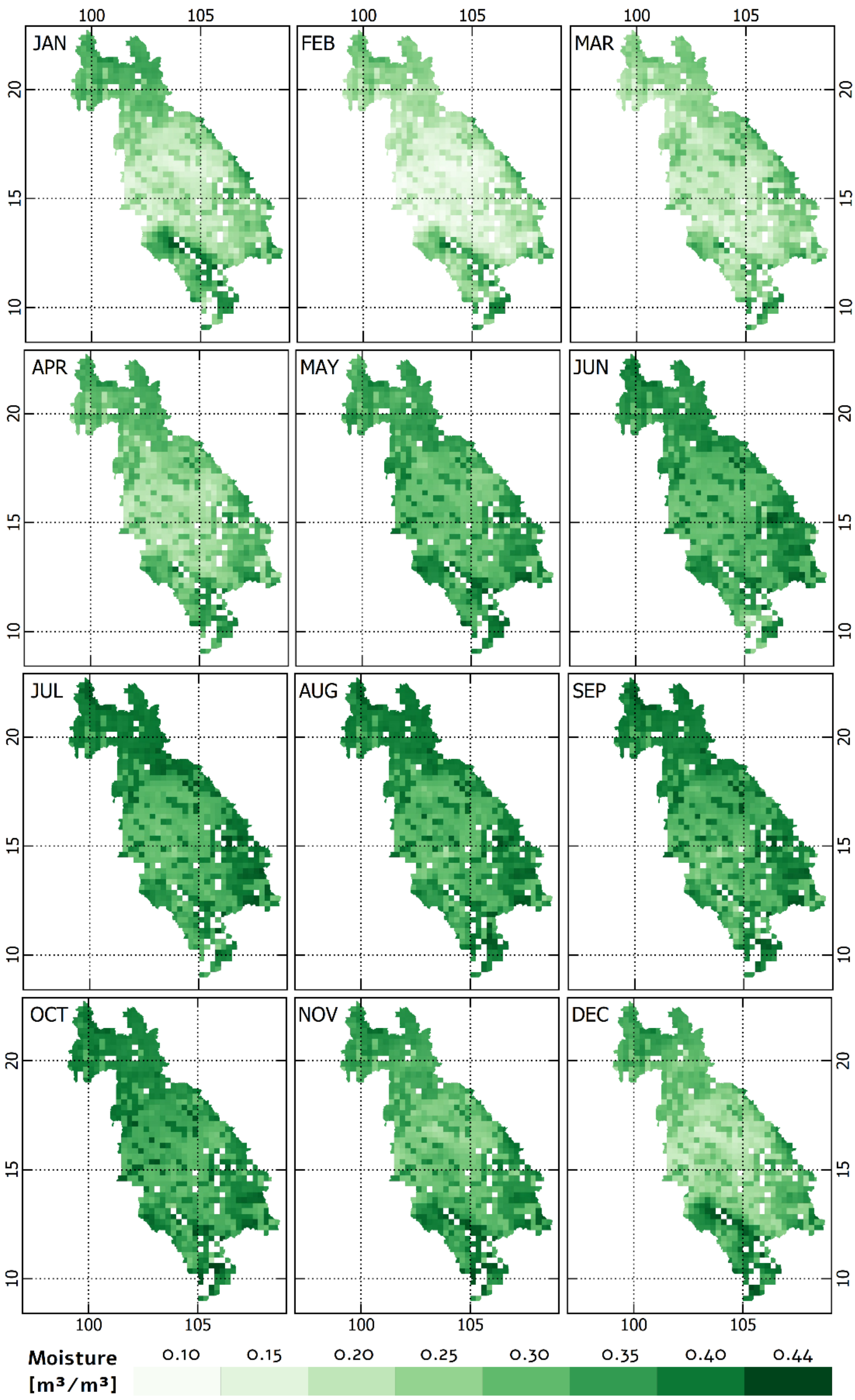


Figure 13: Monthly average (2017) soil moisture for the LMB based on the ESA CCI Soil Moisture product

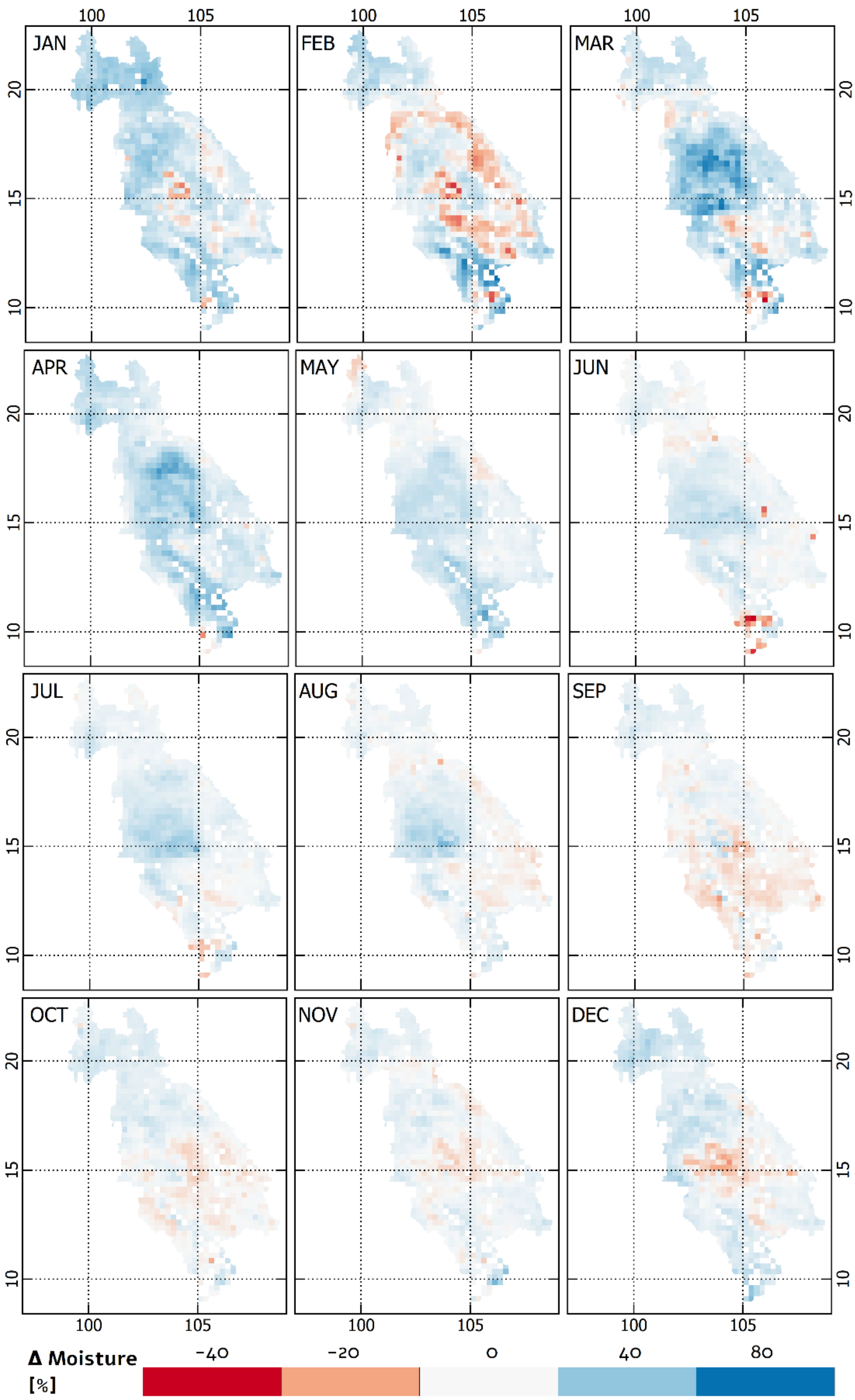


Figure 14: Percent difference of monthly average soil moisture in 2017 compared to the long-term average (2009-2016) in the LMB based on the ESA CCI Soil Moisture product

Figure 14 reveals the actual differences between the long-term monthly soil moisture and the situation in 2017. As can be seen, most months were generally wetter than the long-term average, especially March to July. Only February as well as September to December was partially drier especially around longitude 105 and latitude 15. Please note that the scale in Figure 14 is shifted towards the wetter domain, indicating that blue pixels are twice as wet as red pixels in the same shade are dry.

Using soil moisture in relation to forecasting droughts and agricultural production clearly extends the view from a river perspective to an area perspective. The value of soil moisture observations via satellite can be enhanced when drought indices are used. Drought indices based on soil moisture are calculated from monthly soil moisture data for different lengths of months. The longer the length, the less fluctuations occur. Thus, indices with long periods are able to provide an outlook into the future since change does not happen quickly. It is important to choose the right reference period what is considered as "normal" and the calculation period best representing a certain area and objective. Reference period and calculation period strongly influence results from drought indices and can bias the outcome if not chosen properly. Hindcast experiments are needed to identify these parameters.

The approach shown is not suitable for any kind of near-real-time products, like flash flood support, as the latency at which data is updated is far too long.

2.3.3 Water levels

Water level data from remote-sensing observations provides useful information for assessing reservoir and river water levels in regions or times with a lack of ground observations.

Among others, the Database for Hydrological Time Series of Inland Waters (DAHITI) at the Technical University Munich, provides near real time, satellite-based observations of inland water levels (https://dahiti.dgfi.tum.de/en/). The project uses altimetry data from up to 11 satellites to calculate the temporal change in water levels of water bodies larger than 300m in diameter. DAHITI includes 1729 water-level time series distributed over all continents which are freely available after registration. The product has been available with a latency of about 1 day to one month from 2002 onwards in time steps from 1 day to 31 days depending on the satellite overpasses.

Advantages of the dataset are that it covers vast areas and provides data from regions where water level data may otherwise not be accessible. The product is available free of charge. Disadvantages are the relatively low absolute accuracy in comparison to ground-based observations (about 3-36cm in lakes, 8-114cm accuracy in rivers), lack of full coverage because the satellites used do not cover the whole globe seamlessly but in tracks that have a certain spacing.

The Mekong's 26 stations, including lakes and reservoirs, are available online (https://dahiti.dgfi.tum.de/en/virtual_stations/asia), though not all are updated. Figure 15 shows the satellites used for deriving the water level in the Tonle Sap (Figure 16). A second example location in the Mekong is provided at Kampong Chan (Figure 17). As can be seen from both figures, maximum water levels in 2017 were about average compared to the historical period, while minimum water levels were above average, confirming the assessment from the soil moisture analysis of wetter than average conditions in the LMB.

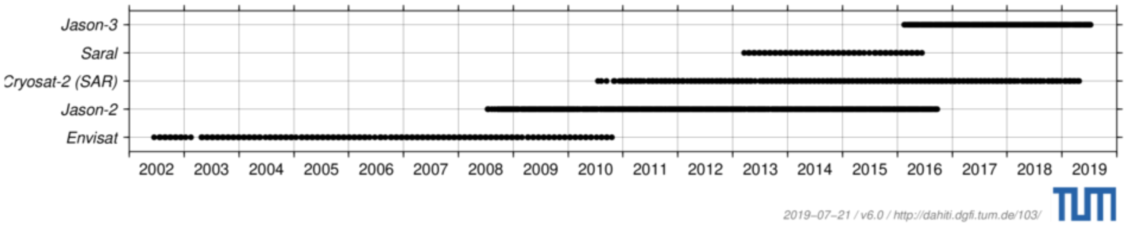


Figure 15: Satellites used in DAHITI during different time periods for deriving the water level of the Tonle Sap

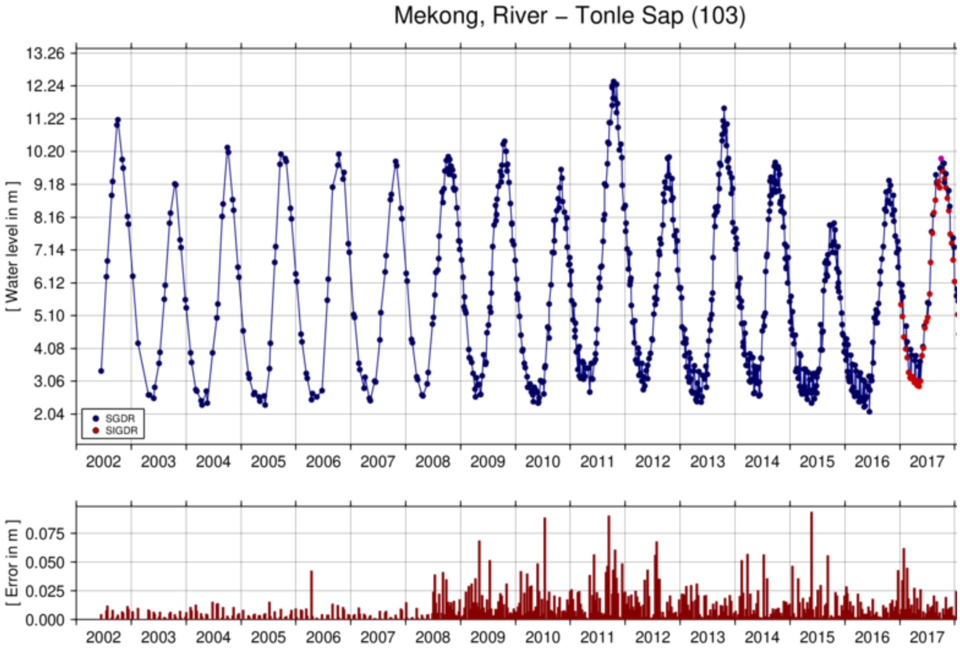


Figure 16: Tonle Sap water level from the DAHITI database (upper diagram) including the estimated error bounds (below)

Comparing the satellite derived water levels with observed records results in a surprisingly good fit.

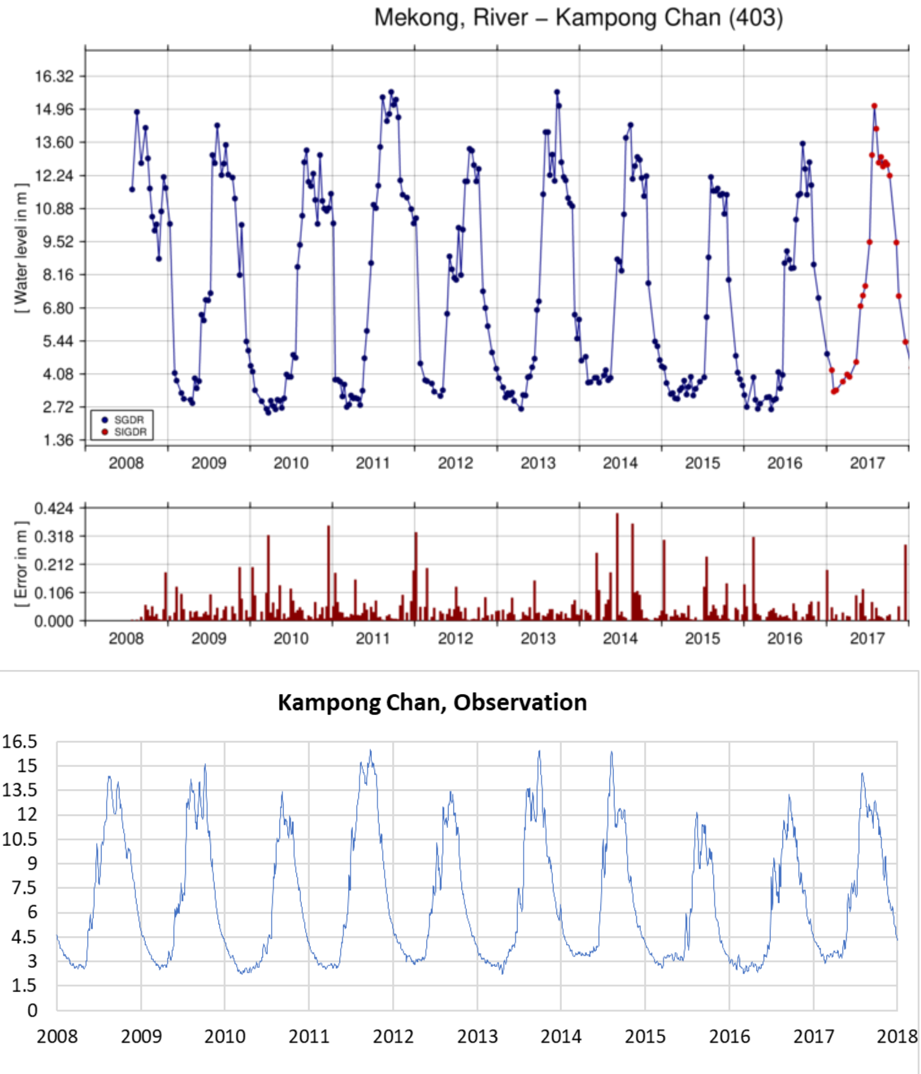


Figure 17: Kampong Chan water level from the DAHITI database (upper diagram) including the estimated error bounds (below) and observed records (bottom)

2.3.4 Monitoring network

MRCs monitoring network was described in detail in the AMFR 2015 (MRC, 2018a) and information is only updated here. The network includes ground-based, manual daily precipitation data provided by the National Line Agencies (Cambodia 63 stations, Lao 45 Stations, Thailand 14 stations, Vietnam 45 stations). Data is received every morning from Member Countries as 24-hour rainfall sums. China now supplies data from two stations during the wet season based on a Memorandum of Understanding. In addition, 45 HYCOS telemetry stations provide automatic readings in 15min observation intervals. Data quality might be impacted by the following points:

- Due to the fully manual data collection and transfer process, data may contain gaps
- Not all stations are continuously updated and maintained
- The telemetry system in Lao is currently not operational
- The number of stations for the Thai and Chinese part of the catchment is low

Therefore, satellite data is used in addition to fill gaps.

Weather radars are an important source of precipitation observations for flash flood activities. While the WMO wishes to improve the situation, Vietnam currently has 7 weather radars, Thailand 26, Laos 1 or 2, and Cambodia 1.

2.4 Forecasting

Forecasting is an important approach to prepare, deal with, and manage extreme hydrological conditions. While flood and flow forecasting are more common approaches that are applied in many regions (including the Mekong) as well as globally, operational drought forecasting is more of an emerging technology. The main difference between flow-related and drought forecast is the spatial coverage. While floods, including flash floods and river flows are forecasted for streams and rivers, droughts have to be forecasted covering total surface areas of the region of interest.

This chapter is divided in three sections where (1) the tools in place at MRC are briefly summarized and explained, (2) drought activities that are planned by MRC are explained, and (3) innovative technologies for forecast and early warning are presented.

2.4.1 MRC Tools

Existing forecasting tools at MRC are the River Flood Forecasting System (RFFS) and the Flash Flood Forecasting System. In 2017, a drought forecasting system was in development for the Mekong with its release in 2018.

2.4.1.1 Flood Forecasting System

The MRC RFFS was described in detail in the AMFR 2015. Therefore, only a condensed summary and future plans and enhancements of the system are provided here. The RFFS is operated at the Regional Flood and Drought Management Centre (RFDMC) in Phnom Penh in two different modes: During the flood season from 1 June to 31 October, daily forecasts of the Mekong's water level are issued with a lead time of 5 days. Mode two covers the dry season from 1 November to 31 May with weekly forecasts issued with a 7-day lead time.

An overview flow chart of the system is provided in Figure 18: The system utilizes daily satellite rainfall estimates (SRE) and 7-day forecasts from GFAS (NOAA) as well as the data obtained from MRC's monitoring network (Chapter 2.3.4). The data is used in three different models linked to the Delft FEWS forecasting platform: The URBS hydrological model, the ISIS 1D hydraulic model, and a regression program. URBS predicts flow and water level at 13 stations in the upstream region of the LMB (740,000km^2 with 2217 sub-basins) while ISIS and the regression approach provides forecasts at 9 stations in the downstream region. MRC RFDMC issues different flood forecasting products: These are rainfall distribution maps in raster format, bulletins that summarize the current and predicted conditions at the 22 Mekong flow stations and notifications in case of abnormal flow conditions.

Challenges and needs for further improvement of the system were identified as:

- Obtaining more detailed information regarding reservoir releases, also from the Chinese part of the Mekong basin
- Increasing the number of rainfall stations, improving the satellite rainfall inputs (e.g. bias correction) and using multiple rainfall sources
- Updating the rating curves to increase accuracy when calculating discharge from water levels
- Finding suitable substitutes for occasions when the NOAA forecasting system is not operational (which is actually a rare case)
- Improving the in-time delivery of hydro-meteorological data
- Improving and supporting the development of forecasting at Mekong tributaries at the national level
- Improving the calibration of the models for varying discharge conditions

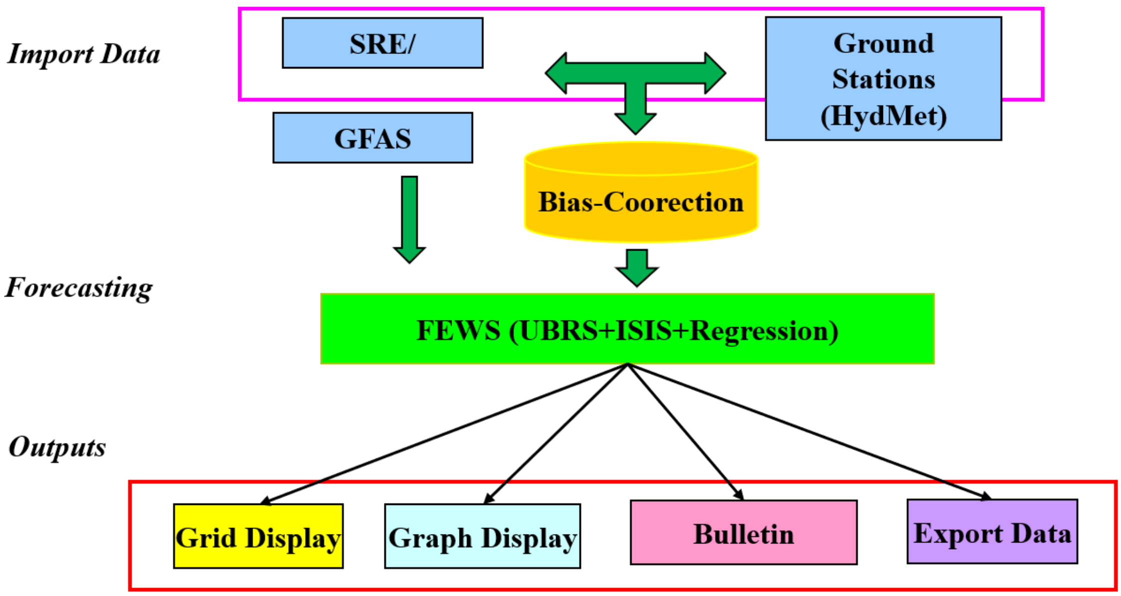


Figure 18: Mekong RFFS flow chart and operation (Khem, 2019)

2.4.1.2 Flash Flood Forecasting System

Since 2009, the MRC has been running the MRC Flash Flood Guidance System (MRCFFGS) as a diagnostic tool to analyse events that have the potential to initiate flash floods (e.g., heavy rainfall, rainfall on saturated soils. The development of the system started in 2005 and was completed in August 2009. The development was performed hand-in-hand with capacity building for the MRCFFGS operators at 4 National Line Agencies.

In late 2009, the computational and dissemination servers for the MRCFFG system were installed at the former MRC Regional Flood Management and Mitigation Centre (RFMMC) in Phnom Penh, Cambodia, which is now the Regional Flood and Drought Management Centre (RFDMC). The system allows the line agencies of the MRC Member Countries and the RFMMC to get access to the FFG products for training as well as for operational purposes. The system enables rapid evaluation on the potential for a flash flood for any location inside the LMB.

Since the system became operational an annual evaluation report on the MRCFFG system was prepared to assess the performance of FFGS for the detection of the risk areas of potential flash flood districts in Cambodia, Lao PDR, Thailand, and Viet Nam. The last evaluation report was issued on March 2018 (MRC, 2018).

A recurrent task is the evaluation of the flash flood guidance products based on two concepts:

1. The first concept evaluates the feedback from users or from other sources such as the media or the press about the FFG System.
2. The second concept evaluates the FFG System through the recorded water levels that are available in the operational database of RFDMC. Where water level stations are available, the FFG results can be evaluated by studying the changing (rising) water level records of stations located in the downstream part of sub-catchments.

MRCs flash flood guidance system was described in detail in the AMFR 2012 (MRC, 2015) and the AMFR 2016 (MRC, 2018b). The system is operational at MRC and the forecasts are available online from the MRC website (http://ffw.mrcmekong.org/ffg.php).

The flash flood warnings are supplied on the website for interested stakeholders to use. Further dissemination and actions are the responsibility of the respective countries. Feedback on the usefulness of the system (e.g. successful warnings, increased levels of preparedness, reduction of damages, evacuations) are requested within the annual reports from the national experts. In the case of the dam break in Lao PDR in September 2017, MRC received information of an expected flash flood. This information was distributed further by MRC via email and the flood bulletin. However, preparing for a dam break is extremely time-sensitive and requires an up-to-date Emergency Preparedness Plans (EPP) in which MRC is just one stakeholder among others. An EPP must contain accurate flood, flood hazard and flood action maps and a clear call-down tree. The call-down or notification tree must include authorities and task forces down to local village heads. The EPP works as expected if and when all parties are clear about their role and responsibility with respect to their obligation to notify others and to take actions prior, during, and after an emergency.

2.4.2 MRC's drought activities

MRC is aware of the need for drought monitoring, management and forecasting in the LMB. The previously named RFMMC (Regional Flood Management and Mitigation Centre) in Phnom Penh was renamed to RFDMC (Regional Flood and Drought Management Centre) and now also hosts MRC's Drought Management Team. Droughts are a serious threat, especially for farmers and their livelihoods, but also in a wider sense in terms of food security.

MRC RFDMC has ongoing drought monitoring and forecasting activities. The main initiatives are the development of the Drought Management Strategy (DMS, from 2020-2025) and the drought forecasting system. The DMS is divided into five sections (MRC, 2019):

1) Indicator monitoring which includes the observation of drought-related processes such as meteorological and hydrological water fluxes, water use, water storage in soil, and groundwater as well as salinity.
2) Drought forecasting and development of the early warning system.
3) Capacity building by assessing drought indicators, drought risk and vulnerability as well as adaptation and improved management for more efficient water resources planning.
4) Developing mitigation measures in collaboration with national and regional institutions through managing water demand and issuing guidelines on drought adaptation.
5) Information sharing and dissemination of collected and generated drought data.

The current stage of drought monitoring and forecasting at MRC for the LMB is provided here http://droughtforecast.mrcmekong.org/maps/ and also referenced to in 2.2.2.

2.4.3 Innovative technologies for forecasting and early warning

Innovative approaches in world-wide forecasting and early warning are highly diverse. For example, spatial coverage ranges from single catchments to global coverage, forecasts from days to seasons, different types of data ae utilised, and systems are designed for a variety of purposes and users. An overview is provided in Table 3. These approaches require suitable input data, which is provided in Table 2 and Table 4.

Important input data for forecasting and early warning are Numerical Weather Predictions (NWP). A summary of products (both free and commercial) is provided in Table 2. Satellite- and ground-based hydro-meteorological datasets (Table 4) are used for calibrating hydrological models to historical conditions and for bias-correcting forecasting data. Both groups of input data are important for forecasting and early warning using models, and can be used as a reference for extending forecasts in the LMB.

Table 2: Available data for hydrological forecasting

Name	Short description	Source
CFSv2	Hourly to monthly climate forecasts on 56km grid for 9-month lead time	https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/climate-forecast-system-version2-cfsv2#CFSv2%20Operational%20Forecasts
HRES	Climate forecasts of the ECMWF on 0.1deg grid for 10-day lead time (**check access costs**)	https://www.ecmwf.int/en/forecasts/datasets
EPS	51 ensemble members of the ECMWF forecasts (**check access costs**)	https://www.ecmwf.int
ESP	Forecast method using historical data only: Simulation with actual data up to the current day and forecasting through simulating ensembles from historical climates	http://ozewex.org/tracing-the-origins-of-ensemble-streamflow-prediction
EUROSIP	Multi-model average seasonal forecasts of the ECMWF in 2.5deg for up to 6-month (**check access costs**)	https://www.ecmwf.int/en/forecasts/datasets/set-viii
GEFS	21 ensemble members of the GFS forecasts	https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-ensemble-forecast-system-gefs
GFS	3-hourly climate forecasts on 28km grid for 7 days, on 70km for 16 days	https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs
ICPAC	10-day, monthly and seasonal climate forecast bulletins for the Greater Horn of Africa region	http://www.icpac.net
SEAS	Seasonal forecasts of the ECMWF in monthly time step in 0.4deg with 7-month lead time (**check access costs**)	https://www.ecmwf.int/en/forecasts/datasets/set-v
Teleconnections	Established links between long-term climate conditions (e.g. SST, ENSO) and future local precipitation patterns elsewhere	https://www.ncdc.noaa.gov/teleconnections
WRF	Weather forecast model that needs to be adapted and run for the region of interest	https://www.mmm.ucar.edu/weather-research-and-forecasting-model

Table 3: Summary of selected forecasting systems and their properties (Kiesel, 2018)

Forecast System Name and Location	Status			Lead-time				Coverage				Data				Methods			Users			
	Research	Operational (internal)	Operational (online)	<7 days	<20 days	<6 month	>6 month	Basin	Country-wide	Transboundary	Global	Teleconnections	Ensemble Streamflow	Deterministic NWP	Ensemble NWP	Discharge regression	Hydrological Model	Routing model	Flood	Drought	Reservoir operation	Shipping, irrigation, mining
GloFAS - Global [A,B]			x			x					x				x		x	x	x			
GLOFFIS - Global [B,C]			x		x						x				x		x	x	x			
E-Hype - Europe [D]			x		x					x				x			x	x	x			
EFAS - Europe [E]		x			x					x					x		x	x	x			
EDO - Europe [F]			x		x	x				x					x		x			x		
HEFS - continental USA [B,G]			x	x	x	x	x		x			x			x	x	x	x	x			
AFFS - continental Africa [H]	x				x					x					x		x	x	x			
Short Term - Yellow River Basin [I]		x		x				x						x		x	x	x	x	x		
Short Term - Benue Basin [J]	x			x						x				x			x	x	x			
KJ-IFS-OPT - Niger Basin [K]		x		x		x				x				x			x	x	x		x	
Hydromax - Meuse River [L]		x		x						x				x		x	x		x			
Seasonal Forecast - Yakima Basin [M]	x						x	x				x										x
Forecasts at the Zambezi River [N,O,P]	x			x						x		x		x			x	x	x		x	
FEWS - Australia [B,Q]			x	x		x			x			x		x			x	x	x		x	
FEWS - Mekong [R,S,T,U]			x	x						x				x		x	x	x	x			
FEWS-FOEN - Switzerland [V]		x			x				x					x			x	x	x			
FEWS-Bfg - Germany [W]			x	x						x					x		x	x	x			x
FEWS - Wupper [X]		x		x				x							x		x	x	x		x	
DEWS - Limpopo [Y]	x					x				x		x	x		x		x			x		
TASK - Germany [Z]		x					x	x						x			x	x		x	x	x

A | http://www.globalfloods.eu/glofas-forecasting/
B | Emerton RE, et al. 2016. Continental and global scale flood forecasting systems. WIREs Water 3: 391-418.
C | http://www.globalfloodforecast.com/glossis/index.htm
D | http://riverinfo.eu/
E | https://www.efas.eu/
F | http://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000
G | https://water.weather.gov/ahps/forecasts.php
H | Thiemig V, Bisseling B, Pappenberger F, Thielen J. 2015. A pan-African medium-range ensemble flood forecast system. HESS 19, 3365-3385.
I | EARS, UNESCO-IHE. 2008. Satellite Water Monitoring and Flow Forecasting System for the Yellow River Basin.
J | Haile AT, Tefera FT, Rientjes T. 2016. Flood forecasting in Niger-Benue basin using satellite and quantitative precipitation forecast data. IJAEOG 52: 475-484.
K | http://www.poyry.at/sites/www.poyry.at/files/inflow_forecasting_system_operational_planning_tool_kainji_nigeria.pdf
L | Bastin G, Moens L, Dierickx P. 2009. On-Line river flow forecasting with 'Hydromax'. Saint-Malo, France.
M | Opitz-Stapelton S, Gangopadhyay S, Rajagopalan B. 2007. Generating streamflow forecasts for the Yakima River Basin. Journal of Hydrology 341: 131-143.
N | http://v-web002.deltares.nl/fewsprojectviewer/projectviewer/projectdata/Operational%20Reservoir%20Management%20-%20Zambezi%20River.pdf
O | HYDROC. 2013. Responding to Climate Change in Mozambique, Phase II-Component Water. DSS Flood Extension and Real Time Pilot.
P | World Bank. 2010. The Zambezi River Basin – A Multi-Sector Investment Opportunities Analysis. Volume 3. State of the Basin.
Q | http://www.bom.gov.au/water/7daystreamflow/#panel=forecasts
R | Plate EJ. 2007. Early Warning and Flood forecasting for large rivers with the lower Mekong as example. J. Hydro-Environment Research 1: 80-94
S | http://ffw.mrcmekong.org
T | MRC. 2018. Long Range Streamflow forecast and Annual Flood Report.
U | http://v-web002.deltares.nl/fewsprojectviewer/projectviewer/projectdata/1455022561-PB_FEWS-Mekong.pdf
V | http://content.oss.deltares.nl/fews/files/National%20Flood%20Forecasting%20System%20Switzerland%20(FEWS-FOEN).pdf
W | https://oss.deltares.nl/c/document_library/get_file?uuid=ddc0654d-3f39-41a3-ac51-7cfbd29c842f&groupId=145641
X | www.wupperverband.de
Y | Trambauer W. et al. 2015. Hydrological drought forecasting and skill assessment for the Limpopo River Basin, southern Africa. Hydrology and Earth System Sciences 19: 1695-1711.
Z | http://task.sydro.de/en/

Table 4: Historical and near real-time global weather data for hydrological modelling

Name	Short description	Lag time	Source
CFSR	Past CFS climate forecasts merged with observations to obtain historical re-analysis data on a 80km grid (1979-present)	app.5d	https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/climate-forecast-system-version2-cfsv2
CHIRPS	Precipitation based on satellite and ground stations in 0.05deg resolution (1981-present minus 3 weeks)	app.5d	http://chg.geog.ucsb.edu/data/chirps/#_FAQ
ERA-Interim	Past climate data forecasts merged with observations to obtain historical re-analysis data on an 80km grid (1979-present)	90d	https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim
EWBMS	METEOSAT-based climate data merged with WMO observations (1982-present) (**check access costs**)	account required	https://www.ears.nl/products-and-services/data-products-for-climate-water-and-food
GPCC	Global Precipitation Climatology Centre various products from monthly to daily time step	1 mon	https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html
GPCP	Merging various satellite-based products and gauge data to a 1-degree precipitation grid (1996-present)	60d	https://climatedataguide.ucar.edu/climate-data/gpcp-daily-global-precipitation-climatology-project
GPM	world-wide 3-hourly near-real-time observation of precipitation on a 5km grid (2015-present)	1-4hr	https://www.nasa.gov/mission_pages/GPM/overview/index.html
GRACE-FO	Monthly grids of storage changes of large water masses derived from gravitational observations (2009 - present)	currently still unknown	https://directory.eoportal.org/web/eoportal/satellite-missions/g/grace-fo
RFE	Uses Meteosat, Global Telecommunication System and WMO ground data (2001-present)	app. 5d	https://earlywarning.usgs.gov/fews/product/48
TAMSAT	African precipitation based on satellite and ground stations on 4km grid (1983-near present)	app. 5d	https://www.tamsat.org.uk
TIGGE	Archive of ECMWF's weather forecast (2006-present)	2d	https://www.ecmwf.int/en/research/projects/tigge
TRMM	Predecessor of GPM, providing 3-hourly precipitation data on a 25km grid (1998-2015-present)	1-4hr	https://pmm.nasa.gov/trmm
MOD16A2	MODIS real time actual evapotranspiration in 8-day time step	30d	https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/6/MOD16A2/2018/?process=ftpAsHttp&path=allData%2f6%2fMOD16A2%2f2018

An innovative approach for seasonal drought forecasting is the TASK research and application project (see also Table 3) (Lohr, Herber, Froehlich, & Richter, 2018). TASK is a German acronym and means 'Reservoir adaptation strategy to climate change' and was originally conceived for reservoir operators but was subsequently expanded for drought forecasts for rivers and areas. The core of the project is a hybrid approach that combines indices and NWP+HM, which shows promising results. The advantage lies in the consideration of the persistence and inertia of hydrological processes that form the basics of the indicators in combination with forecasted soil moisture and streamflow derived from spatially distributed NWP+HM. Bias correction relies on ground stations and thus, the more meteorological ground stations are available in the catchment of interest, the better the results. Another constraint is the period for calibration. The longer the calibration period, the better the robustness of the approach. The TASK research project is entering into phase 2, where its seasonal drought forecast approach is used as basis for preparedness towards contingency planning. Results from TASK for a catchment with approximately 3000 km^2 in Germany is depicted below.

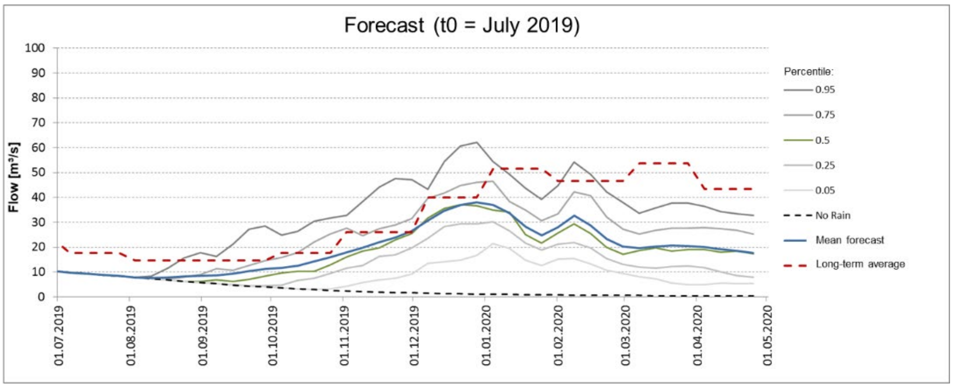


Figure 19: Forecast from July 2019 for 9 months for River Werra, Germany

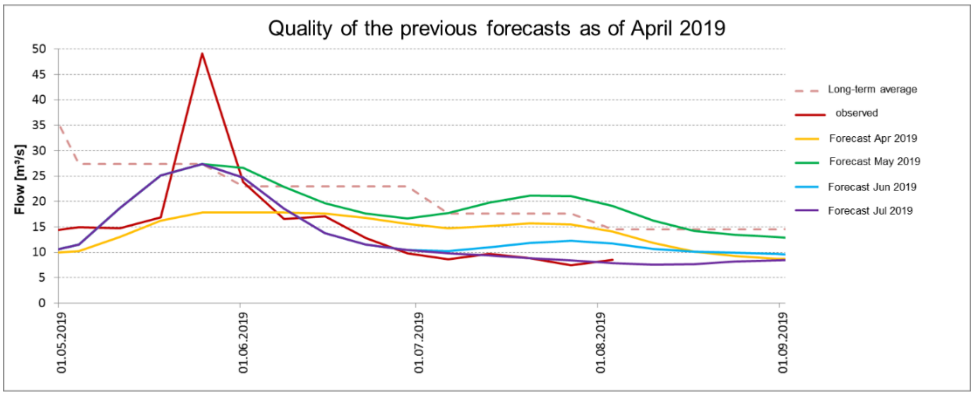


Figure 20: Quality of forecasts from April to July 2019 for River Werra, Germany

TASK is suitable for low flow periods. The ability to detect high flow events is limited since the approach runs on a monthly basis and does not allow for inner-monthly events.

2.4.4 Long-range streamflow forecast for the LMB

In 2016, a first assessment on long-range or seasonal streamflow forecasts was undertaken (MRC, 2016). The report describes the available data, provides a world-wide review on approaches, defines and applies criteria for identifying suitable methods for the LMB, and preselects applicable methods. The final outcome is a roadmap for implementation given as a step-by-step guide. The report concludes that preference should be given to a hybrid approach based on a) seasonal weather prediction system CFSR, issued by NOAA, together with the application of a hydrologic modelling in combination with b) a stochastic streamflow method. A prerequisite for the hydrological model is the ability to run as a complete water balance and water management model with soil moisture accounting allowing for modelling surface flow components, interflow and baseflow, and releases from reservoir operation. A purely flood oriented model, which relies on accumulated rainfall-surface flow indices (like the SCS approach) turned out to be inappropriate. In addition, applying stochastic streamflow methods can help improve the forecast for the Mekong mainstream.

The report states that the predictive performance for the onset of the rainy season was significantly lower compared to the receding part (second half) of the flood season. The quality for predicting flow along the Mekong River after the flood season was good, provided that releases from the Chinese dams are available.

2.5 Modelling

Modelling is an essential part of a forecast since a sufficient depiction of the hydrologic and hydraulic conditions is a prerequisite for issuing realistic forecasts related to droughts and floods. The requirements on the models are vary depending on the type of the forecast, since the models have to be able to allow for the relevant hydrological and hydraulic processes for the respective forecast. However, any model can only be as good as the input data allow. Therefore, the following subchapters give an overview of the required model capabilities and input data from which modelling strategies for flood and drought forecasting can be derived.

2.5.1 Requirements for short- and long-range flood forecasts

Different options exist to forecast short and long-range flooding. For short-range forecasts, this is usually hydrological and hydraulic modelling (HM) coupled to Numerical Weather Prediction (NWP) or streamflow correlation/flow routing. For long-range or seasonal forecasts, these two approaches are extended by teleconnections and index approaches. The most widely used approach is NWP+HM for which the requirements on models and data are outlined here so that the NWP+HM is able to provide forecasts of both short- and long-range situations. In this case, it is important to depict the full hydrological system, including natural water storages (soil, groundwater, lakes) and the operation of reservoirs.

For a hydrological model to be useful in short- and long-range flood forecasting, it has to be calibrated to the prevailing conditions in the area and has to be able to depict the following processes:

- Interception and evapotranspiration
- Surface runoff, infiltration, interflow
- Soil moisture

- Groundwater processes resulting in baseflow
- Flow routing
- Reservoir processes and operation
- Inundation and urban flooding (depending on the area of interest)

Data requirements, typically in hourly, daily- (short range) to monthly- (long range) time step:

- Historical climate (temperature, precipitation), discharge and water levels for model calibration and bias correction
- Real-time observed rainfall
- Real-time observed water level and discharge
- Forecasted rainfall for the period of the forecast (bias corrected)

2.5.2 Requirements for seasonal drought forecasts

Seasonal drought forecasts are either issued as grid-based indexes to depict the whole region of interest or as values of river flows, reservoir and lake water levels. These are generally two different approaches. While maps of regions are depicted through the calculation of drought indices such as SPI or SPEI, seasonal predictions of river flows and water levels are typically based on NWP+HM with meteorological forecasts as input in hydrological models. For the latter approach, it is important to depict the full hydrological system, including natural water storages (soil, groundwater, lakes) and the operation of reservoirs.

For a hydrological model to be useful in seasonal drought forecasting, it has to be calibrated to the prevailing conditions in the area and has to be able to depict the following processes:

- Interception and evapotranspiration
- Surface runoff, infiltration, interflow
- Soil moisture
- Groundwater processes resulting in baseflow
- Flow routing
- Reservoir processes and operation

Data, typically needed on daily or monthly time step:

- Historical climate (temperature, precipitation), discharge, water levels for calibration and bias correction
- Real-time observed rainfall
- Real-time observed water level and discharge
- Forecasted rainfall for the period of the forecast (bias corrected)

2.5.3 Requirements for flash-flood forecasts

Flash floods have been the theme of the AMFR 2012 and therefore, a brief summary of the topic and update is given here. Flash floods can be caused by different processes: intense rainfall in urban areas/sealed surfaces, failure of water infrastructure, highly intensive rain on saturated soils as well as rainfall intensities that exceed the infiltration capacities of the surface and topsoil. These different flash flood mechanisms have in common that the events unfold rapidly, possibly within minutes mostly due to relatively steep gradients, which cause high flow velocities and leave little time for forecasting and for people to prepare or escape. The establishment of a flash-flood forecast and early warning system could give threatened locations and residents valuable lead and preparation time. Despite major efforts and advances to develop such systems, forecasting flash-floods is still the most difficult hydrological prediction. Regardless of state-of-the-art forecasting tools, flash floods are still a deadly danger today, even in highly developed and data-rich countries. The main reasons for this are:

(1) The complexity of flash flood mechanisms with multiple conditions having to occur at the same time, which all have high uncertainty in their prediction, both temporally and spatially.

(2) The lack of very accurate high spatio-temporal resolution rainfall forecasts. The single most important aspect of a flash flood forecast simulation is suitable high-resolution precipitation and weather forecast information.

(3) The high impact of the initial conditions in the models. Continuous simulations need to be carried out to reliably track soil moisture conditions over time and ideally calibrate and update soil moisture conditions through historical and real-time observations. Initiating the model with different antecedent moisture conditions and an ensemble of weather forecasts leads to a range of forecasts with their respective probabilities.

This leads to (4) the difficult balance between selecting thresholds for issuing an alarm (or possible false alarm). A key challenge for any successful, accepted flash-flood forecasting system is the distinction between successful warnings and possible false alarms. Multiple false alarms will reduce trust in the system with the consequence that warnings are ignored.

(5) If a warning is to be issued, dissemination must follow very quickly to generate enough lead-time to get the warning to all people in time.

With any flash-flood forecasting system, it is therefore paramount that all administrators and users understand the possibilities, uncertainties, and limitations of the system as well as the urgency of required action when a warning is issued. Examples of Flash Flood Forecasting Systems exist in the USA (https://www.weather.gov/nerfc/ffg), Europe (https://efas.eu/en) or as the Global Flash Flood Guidance System (http://www.wmo.int/pages/prog/hwrp/flood/ffgs/index_en.php).

Technically, flash flood guidance systems can be based on observation data alone (e.g. near real time observations of soil moisture, infiltration capacity information and rainfall forecasts) or utilizing hydrological models. If a flash flood guidance system includes hydrological models, these have to be able to depict the following processes:

- Surface runoff, infiltration
- Flow routing
- Inundation and urban flooding (depending on the area of interest)
- Updating of initial conditions based on observations or the realistic simulation of evapotranspiration and soil moisture (hot-start)

Data, typically sub-daily and sub-hourly time steps:

- Historical climate (temperature, precipitation), discharge and water levels for calibration
- Real-time observed rainfall (preferably high-resolution ground-based radar data)
- Forecasted rainfall for the period of the forecast

2.6 Monitoring

All records from discharge stations are water levels, which are subsequently transformed to discharge by means of discharge-elevation curve or rating curves. Thus, the quality of the rating curves determines the quality of discharge. Errors in the rating curves directly result in errors of discharge and might lead to wrong interpretations.

Typical errors attributable to rating curves are changes of the cross section and/or changes of the gauge datum. Both error types may either lead to an increase or decrease of discharge depending on the change itself. No matter which direction the change finally is, the consequence is a wrong discharge and thus a wrong flow volume. Sedimentation or erosion is usually the root cause of an error in the rating curve. Therefore, it is necessary to regularly perform flow measurements or to check the cross-section and to recalculate the rating curve with a hydraulic model. In case of very large cross-sections, it is more feasible to update the bathymetry and to run a hydraulic model.

The water levels and discharges along the Mekong mainstream were analysed as to whether indicators for a drift of the water level records are visible. A possible indicator is if: a) the total flow volume has a trend over the years, or b) low flow discharge has a trend but adjacent gauging stations have none.

	Mann-Kendall Trend Test	
Name	Minimum monthly flow volume per year	Total flow volume per year
Chiang Saen	yes	no
Luang Prabang	no	no
Nakhon Phanom	yes	no
Nong Khai	yes	no
Mukdahan	yes	no
Pakse	yes	no
Strung Treng	yes	no
Kratie	yes	no
Phnom Penh Port	yes	no

Only adjacent stations Chiang Saen and Luang Prabang show different test results for minimum monthly flow. While all other stations show a positive trend in minimum flow due to increased releases from dams in the dry season, the test result at Luang Prabang does not confirm this. Comparing minimum flow volume at both stations, the increase at Chiang Saen is obvious while an increase at Luang Prabang becomes apparent only for recent years.

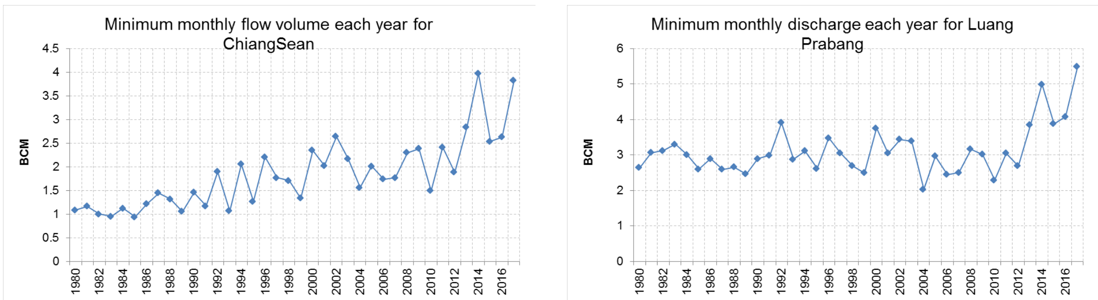


Figure 21: Time series of minimum flow volume at Chiang Saen and Luang Prabang

Rating curves are sensitive and errors in the curve bias results. Regular checks should be performed to exclude errors in the derived discharge time series. However, an update of rating curves does not render previous rating curves useless. Rating curves become part of the time series and period of validity for rating curves must be documented and linked to the time series otherwise a time series cannot be reproduced anymore.

Whether or not the trend analysis shown above proofs a change in the rating curve, it seems appropriate to review and update the curves since the last update dates back to before 2010.

3 THE REGIONAL FLOOD AND DROUGHT SITUATION 2017

3.1 Tropical storms and cyclones

Tropical storms and cyclones affecting the LMB usually make landfall along the coast of Viet Nam before they reach the other Member Countries. Viet Nam is among the five most affected typhoon hot spots in the World (Pham & Vu, 2019). In recent years, the number of cyclones, storms, and tropical depressions in the Western North Pacific Ocean seem to have increased gradually. In addition, the period when tropical depressions and storms are formed seem to have expanded since tropical depressions occurred early in January or February until the end of December.

Table 5: Tropical depression, storms and cyclones in 2017 (source: National Centre of Hydrology and Meteorology, 2018)

Sea region	Date of Occurrence	Storm name	Wind speed level
East Sea	7/1/2017	Tropical depression	Level 6 (39 - 49 km/h)
North West Ocean	10/6/2017	Merbok	Level 9 (75 - 83 km/h)
East Sea	14/7/2017	Talas	Level 10 (110 km/h)
North East Sea	21-23/7/2017	Roke	Level 8 (65 km/h)
North East Sea	27/7/2017	Haitang	Level 9 (75 - 83 km/h)
East Sea	21-29/7/2017	Sonca	Level 8 (65 km/h)
North East Sea	19/8/2017	Hato	Level 14 (140 km/h)
North East Sea	24/8/2017	Pakhar	Level 10 (110 km/h)
North West Ocean	30/8/2017	Mawar	Level 10 (110 km/h)
North West Ocean	3/9/2017	Guchol	Level 8 (65 km/h)
East Sea	10/9/2017	Doksuri	Level 12-15 (133-158 km/h)

Sea region	Date of Occurrence	Storm name	Wind speed level
North East Sea	23/9/2017	Tropical depression	Level 6 (39 - 49 km/h)
North East Sea	7/10/2017	Tropical depression	Level 6 (39 - 49 km/h)
North East Sea	11/10/2017	Khanun	Level 13 (110 - 139 km/h)
South East Sea	30/10/2017	Tropical depression	Level 6 (39 - 49 km/h)
South East Sea	31/10/2017	Damrey	Level 12-15 (133-158 km/h)
East Sea	7/11/2017	Haikui	Level 8 (65 km/h)
South East Sea	16/11/2017	Kirogi	Level 8 (65 km/h)
South East Sea	14/12/2017	Kai-tak	Level 8 (65 km/h)
South East Sea	16/12/2017	Tembin	Level 12 (130 km/h)

The colorized entries in the table are Typhoons and shown in Figure 22. Typhoon Dembin is the exception with formation at the end of December and hitting the southern part of Viet Nam. All tracks of depression, tropical storms, and typhoons are shown in Figure 23.

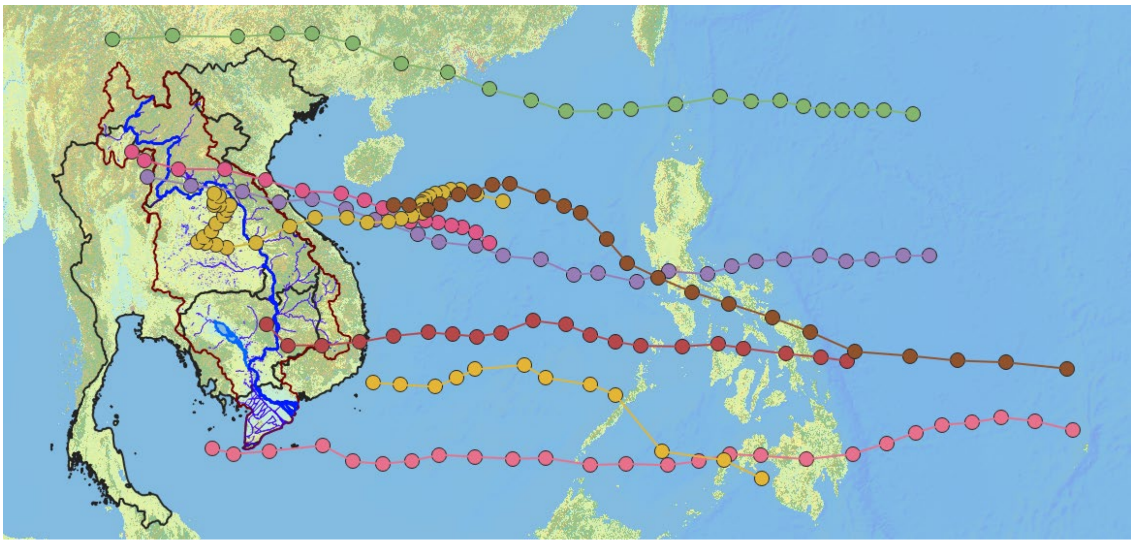


Figure 22: Typhoons in 2017 making landfall and affecting the LMB (source: http://agora.ex.nii.ac.jp/digital-typhoon/year/wnp/2017.html.en)

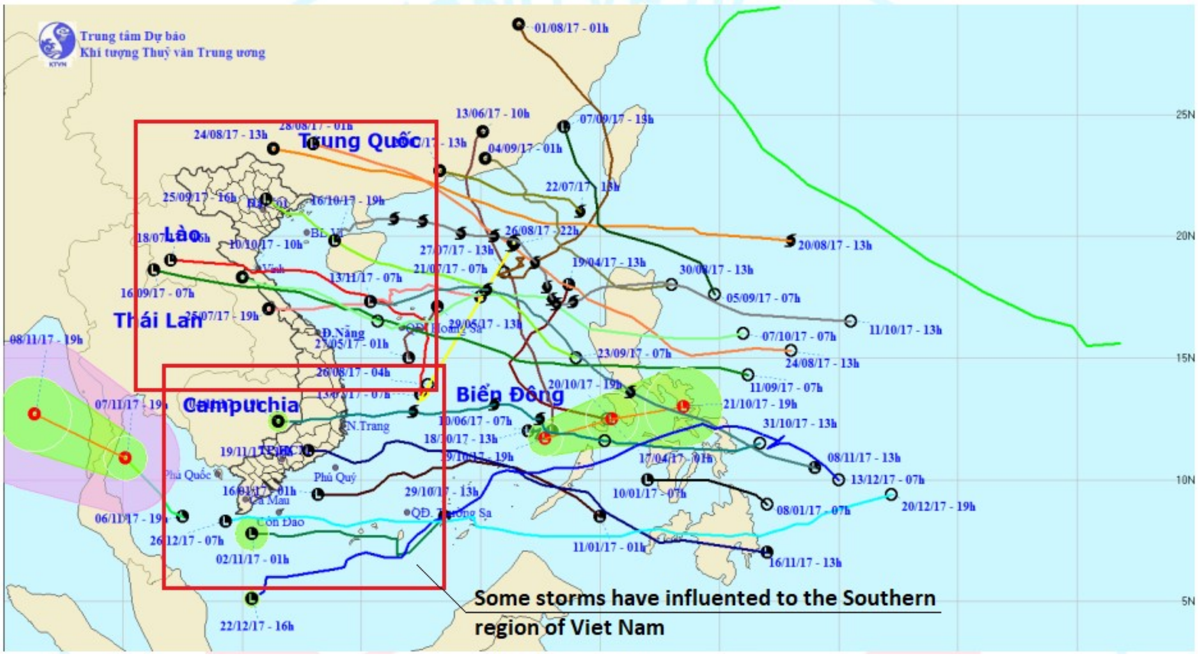


Figure 23: The direction of storms and tropical depressions in 2017 (source: National Centre of Hydrology and Meteorology Forecasting)

3.2 The regional climate during 2017

The Asia land temperature anomalies, published by NOAA, indicate 2017 was the second warmest year since 1910, given the reference period from 1910 to 2000 as it is used by NOAA. The temperature rose at an alarming rate and is likely to intensify extreme hydrological conditions. Excess water and droughts are likely to worsen.

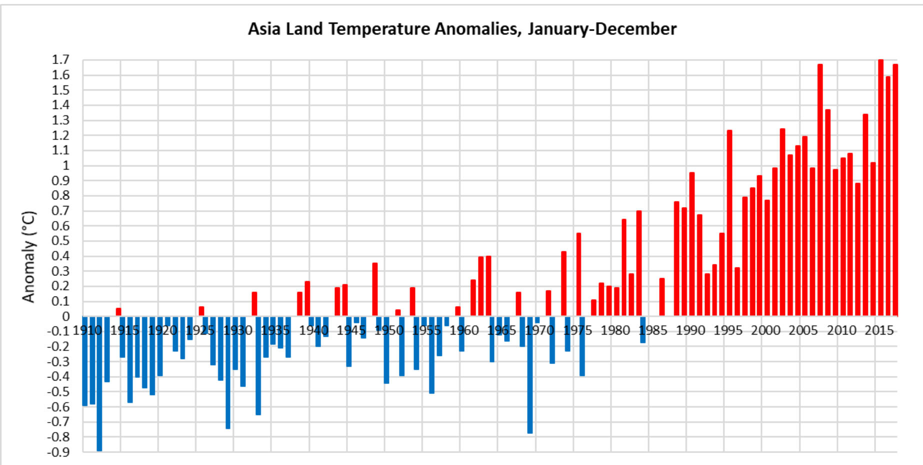


Figure 24: Asia land temperature anomalies, Jan-Dec 1910-2017 (source: NOAA)

3.2.1 Onset and termination of the flood season

A definition of the onset and end of the flood season is given in the AMFR 2006. Mean annual discharge is used as the trigger separating the year into four seasons: (1) dry; (2) transition dry to flood; (3) flood season; and (4) transition back from flood to dry season. This definition is reasonable for natural flow conditions but is difficult when discharge is disturbed by reservoir operation as it is in the case at least for Chiang Saen.

Separating the hydrograph with the definition from 2006 has become somewhat ambiguous. Fluctuations due to reservoir releases are in the range or larger than natural flow patterns. When the flood season starts, Chinese dams commence their filling phase causing a delay of the onset further downstream. With the definition from 2006, the onset and termination of the flood season is given in Table 6.

Table 6: Onset and termination of the flood season using the definition from AMFR 2006

	Onset of flood season			End of flood season		
	historical average	Standard deviation	2017	historical average	Standard deviation	2017
Chiang Saen	Mid Jun.	14 days	11-Jul	End of Oct.	14 days	03-Oct
Vientiane	Mid Jun.	14 days	15-Jul	End of Oct.	15 days	06-Nov
Luang Prabang			12-Jul			04-Dec
Mukdahan			02-Jul			30-Oct
Pakse			07-Jul			27-Oct
Kratie	Mid Jun.	16 days	10-Jun	End of Oct.	12 days	16-Nov

Using the historical average start and end mentioned in AMFR 2006 and 2007, the delay of the start upstream is obvious and diminishes from upstream to downstream. The problem of defining the flood season with the definition from 2006 is shown in Figure 25 with more than one up-crossing and down-crossing at upstream stations.

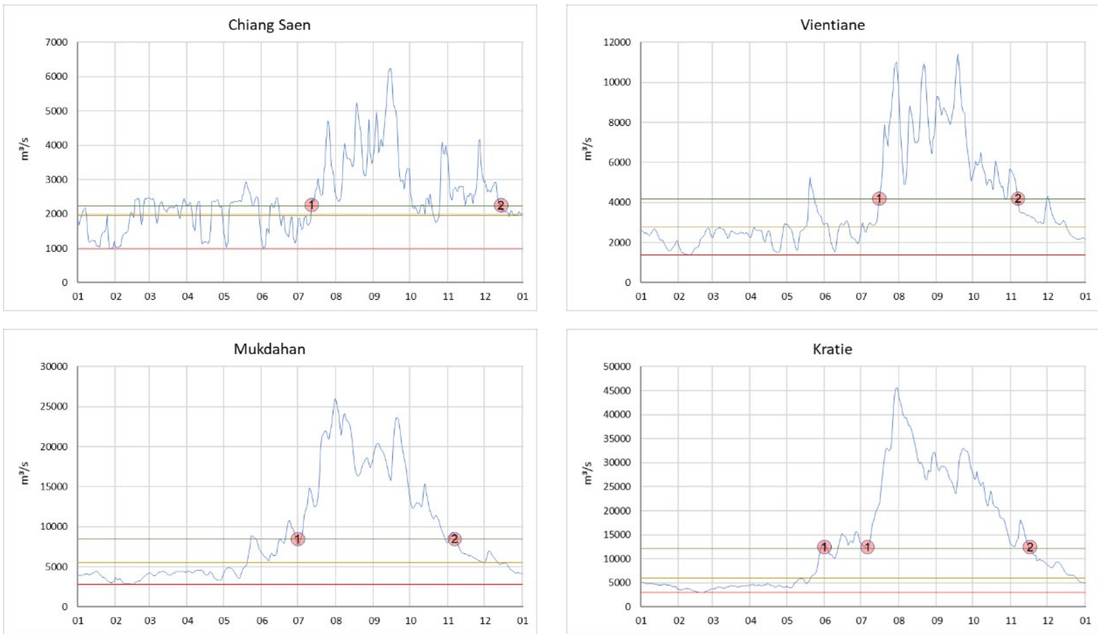


Figure 25: Onset and termination of flood season 2017 at selected stations

3.2.2 Annual Rainfall and monthly rainfall distribution

Monthly cumulative rainfall 2017 is compared with the long-term average based on datasets from the World Bank (1901 to 2015). The data for 2017 was derived from 135 rainfall stations. The available number of stations for each country differs: 48 stations were available from Cambodia including 7 with no-data or errors; 43 from Lao PDR of which 8 had no data or errors; 10 from Thailand with 1 station with errors; and 34 from Viet Nam, including 2 with no data or errors. The number of stations must be kept in mind in conjunction with the respective watershed of the Mekong. While Lao PDR is completely within the LMB, Thailand is not and as such WB's rainfall for overall Thailand might differ from the LMB region. Except for Cambodia, July was the wettest month while all others reflect close to average conditions. The impact of typhoons in October to December reaching or passing Southern Viet Nam is visible.

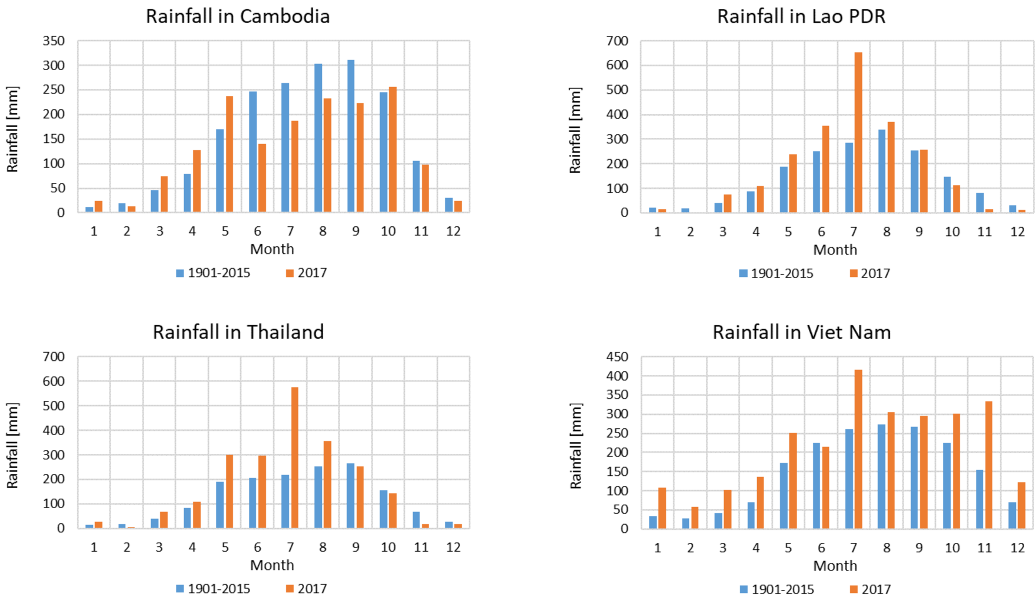


Figure 26: Monthly mean rainfall data 1910-2015 compared with 2017 from 135 stations located within the LMB

Cumulative rainfall and anomaly for the year 2017 are illustrated in Figure 27. The anomaly for 2017 was calculated with mean values from 2006 to 2016.

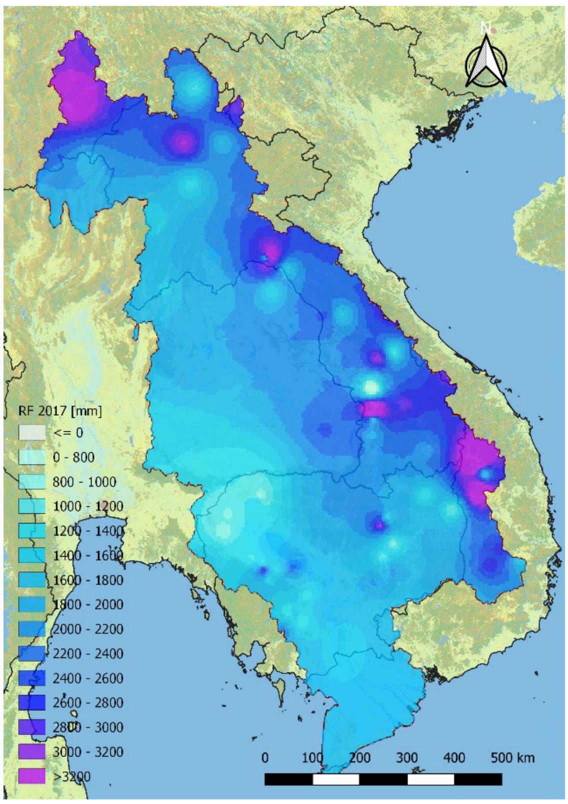


Figure 27: Annual rainfall distribution 2017

The LMB shows close to average or slightly wet conditions in the LMB. Cumulative rainfall for selected stations is presented in Figure 28.

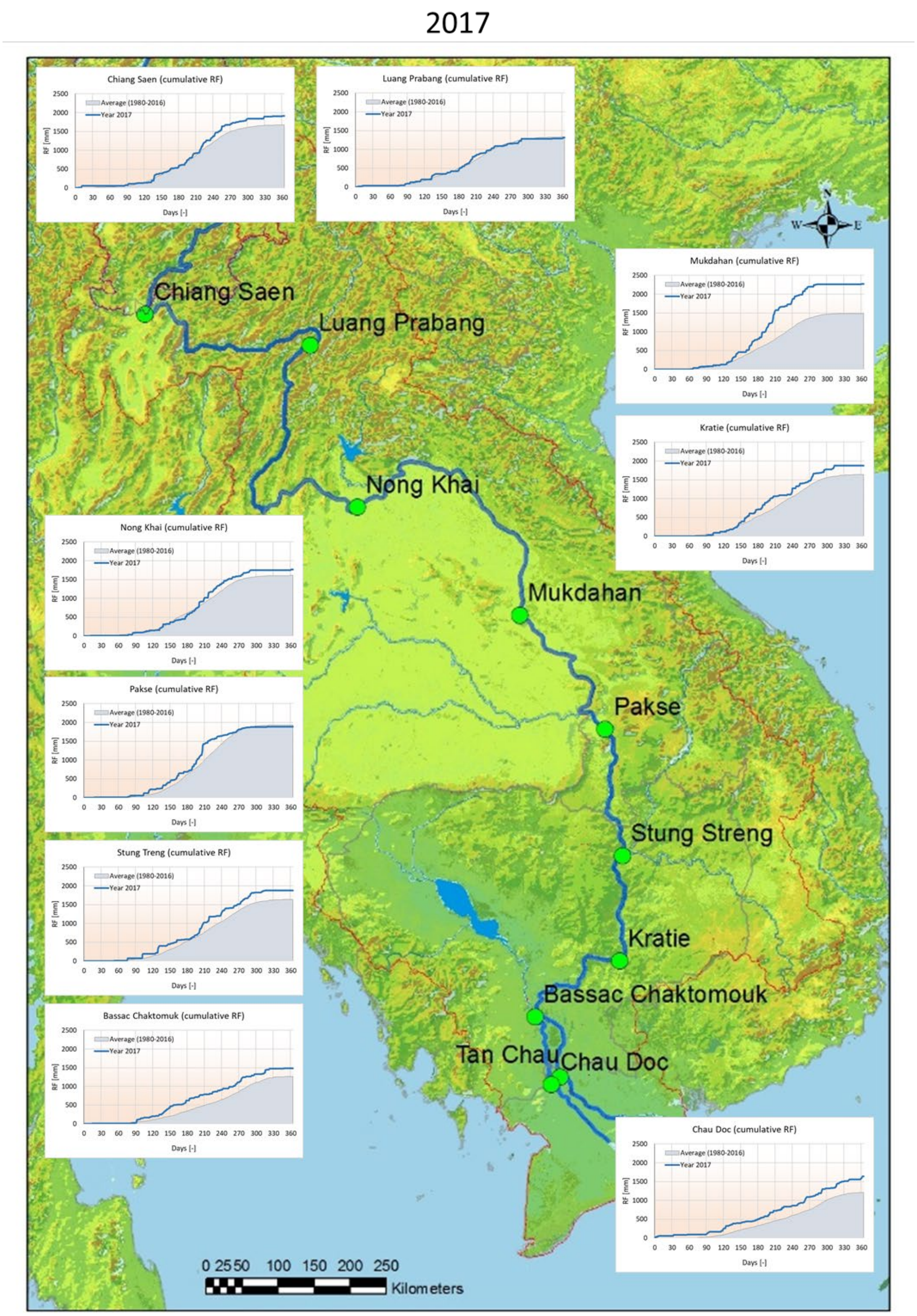


Figure 28: Cumulative rainfall 2017 and long-term averages at selected stations

3.3 The hydrological conditions 2017

The start of the flood season at all stations was very close to normal except for the most upstream station Chiang Saen (see 3.2.1). This reflects the average rainfall conditions. The Mekong Delta and the contribution from the Cambodian Plain and Great Lake are below average. The impact of typhoon Talas is clearly visible as it generated a remarkable peak in July.

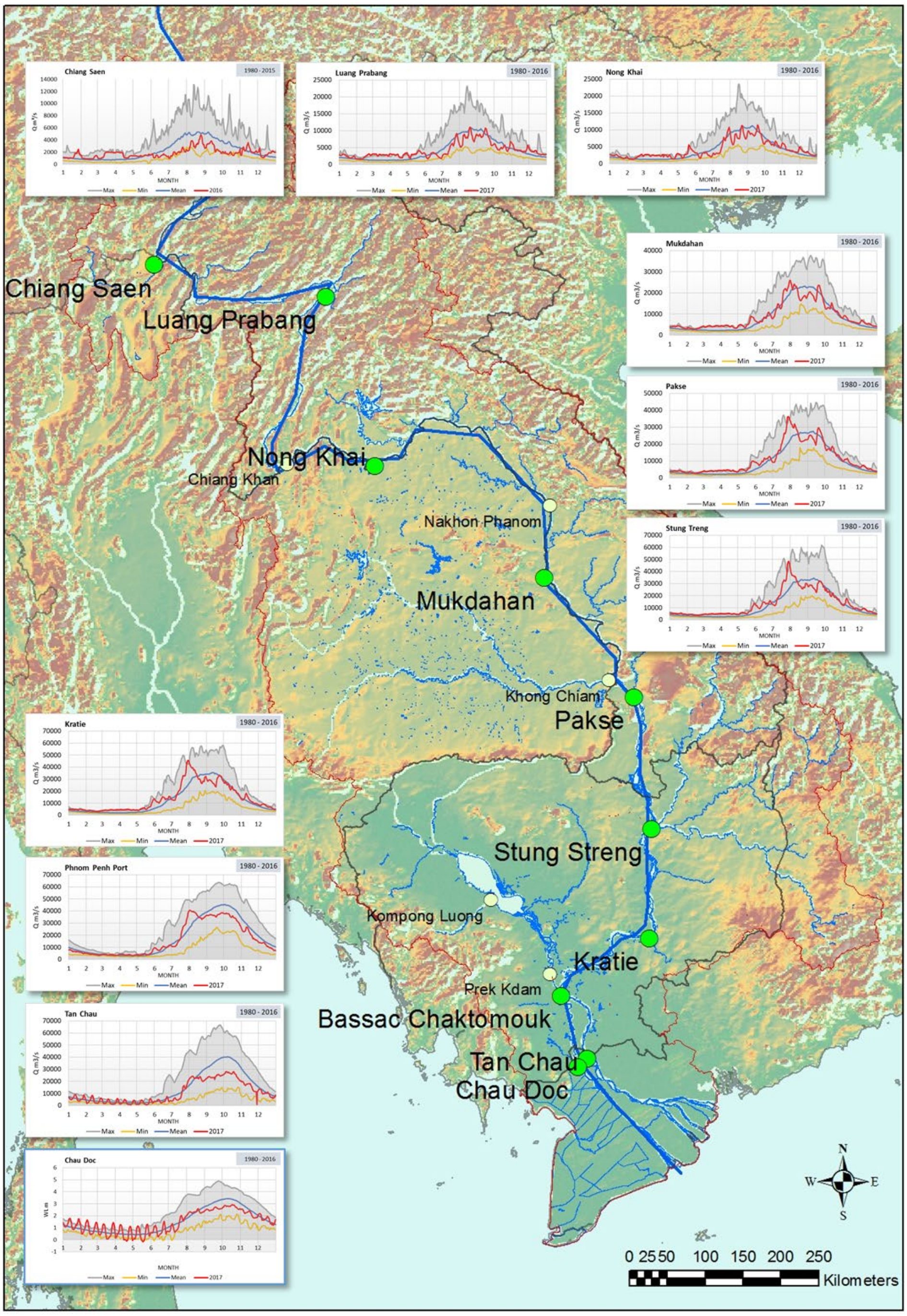


Figure 29: Hydrographs 2017 compared with average/min/max at selected stations

Figure 30 shows a schematic view of the Mekong River. The mean annual discharge volume is illustrated with simple symbols. The width of each element represents the annual volume. Both schematic views use the same scale. The labels indicate the annual flow volume in km^3. Flow from tributaries was calculated from the delta flow volume between adjacent up and downstream stations. Losses are indicated as yellow arrows. A loss occurs if the downstream station from two adjacent stations had less annual volume than the upstream station and the delta between both becomes negative. Two stations were used to calculate total flow volume in the Delta: Tan Chau and Chau Doc. The fading colour indicates the uncertainty of the discharge in tidal influenced areas. The contribution of the Cambodian Plain remains below its average in previous years.

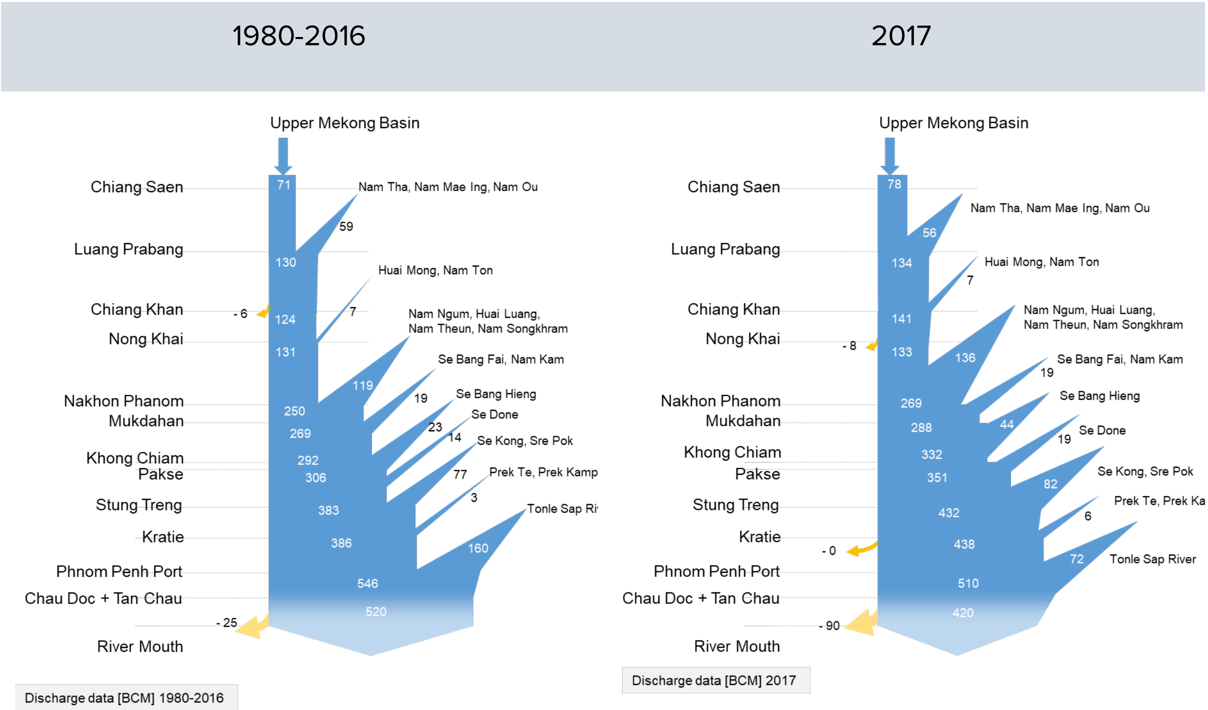
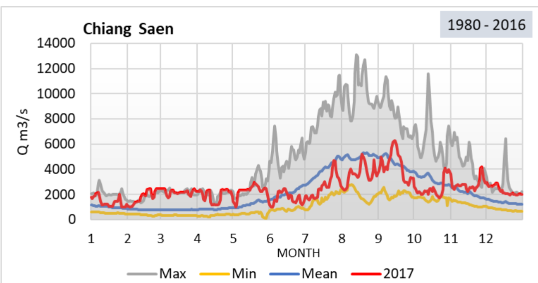
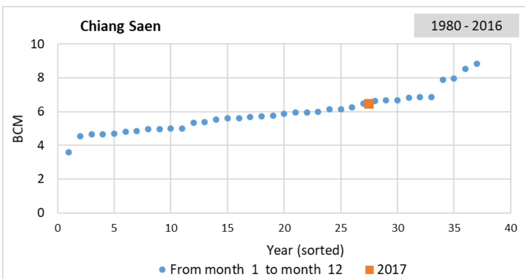


Figure 30: Comparison of annual discharge volume in km^3 (1980-2016) with 2017

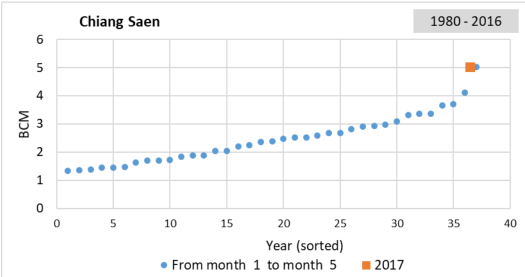
The flood season 2017 can be characterised as follows:

- At Chiang Saen, the hydrograph has almost lost its natural flood pulse. Apart from September and October, releases from the Lancang reservoir system keep a rather constant level throughout the year.

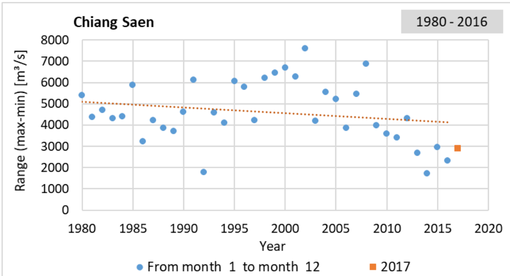


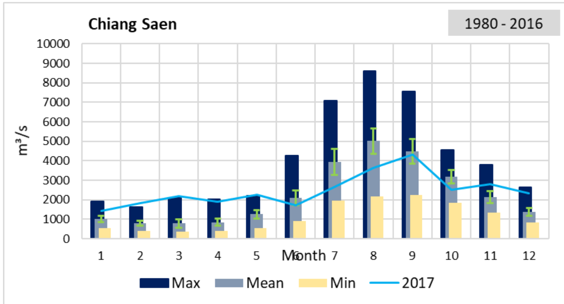


- The flow volume from January to May results in the highest record in 2017.

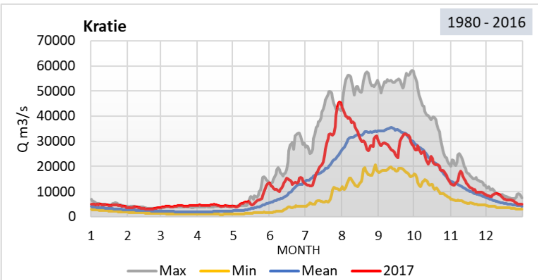


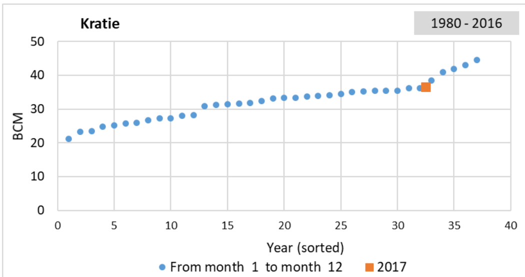
- The range between maximum and minimum discharge throughout the year at Chiang Saen was amongst the lowest ratios ever with a clear downward trend.



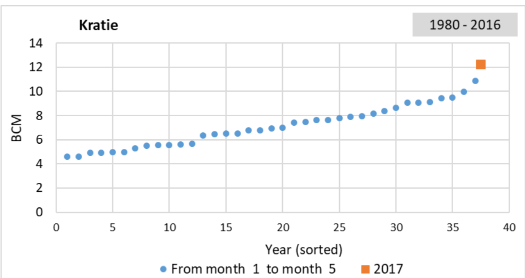


- Kratie's annual flow volume ranks 6th highest in history going back to 1980.



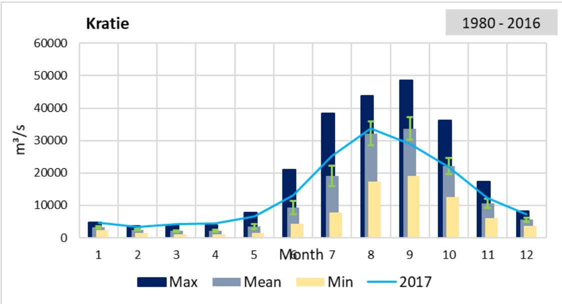


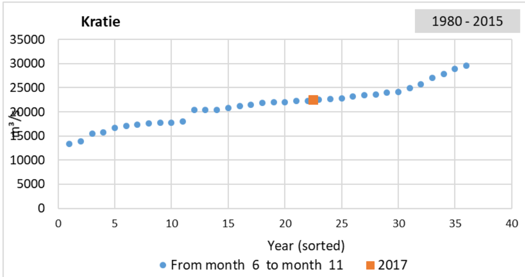
- The flow volume from January to May, however, resulted in the highest recorded since 1980.



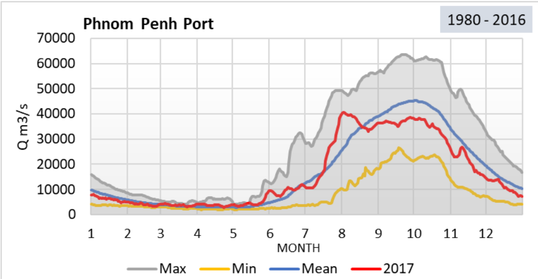
This means that the impact of reservoir releases are still visible.

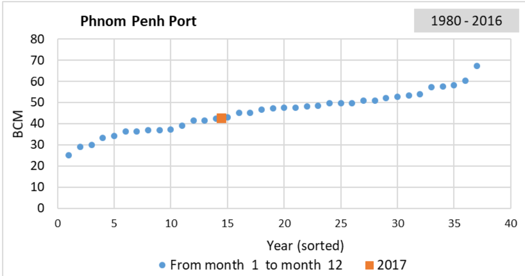
- The flood volume of 2017 was nearly average.



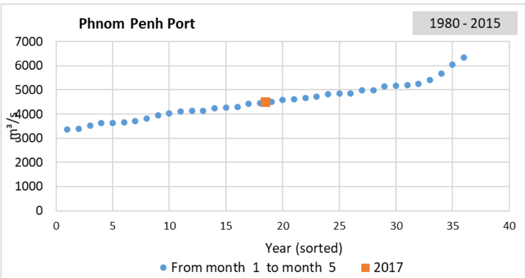


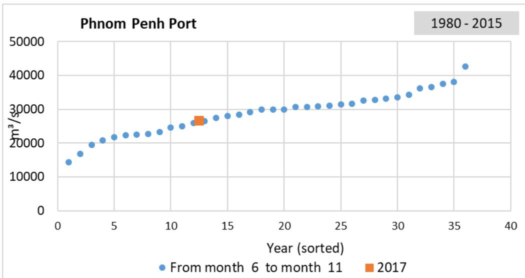
- Annual flow volume at Phnom Penh Port was below average.



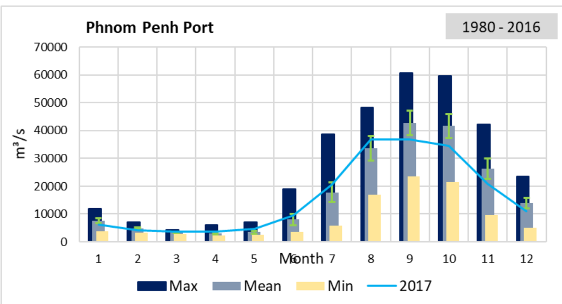


- The flow volume from January to May reached exaclty average conditions, while months 6 to 11 remained below average.





- The range between maximum and minimum discharge also has a decreasing tendency.



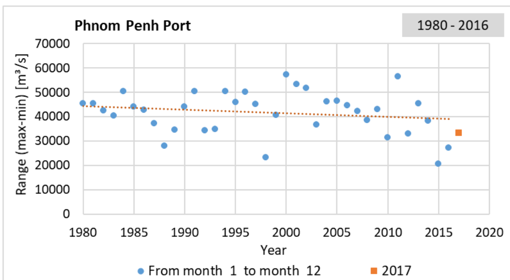
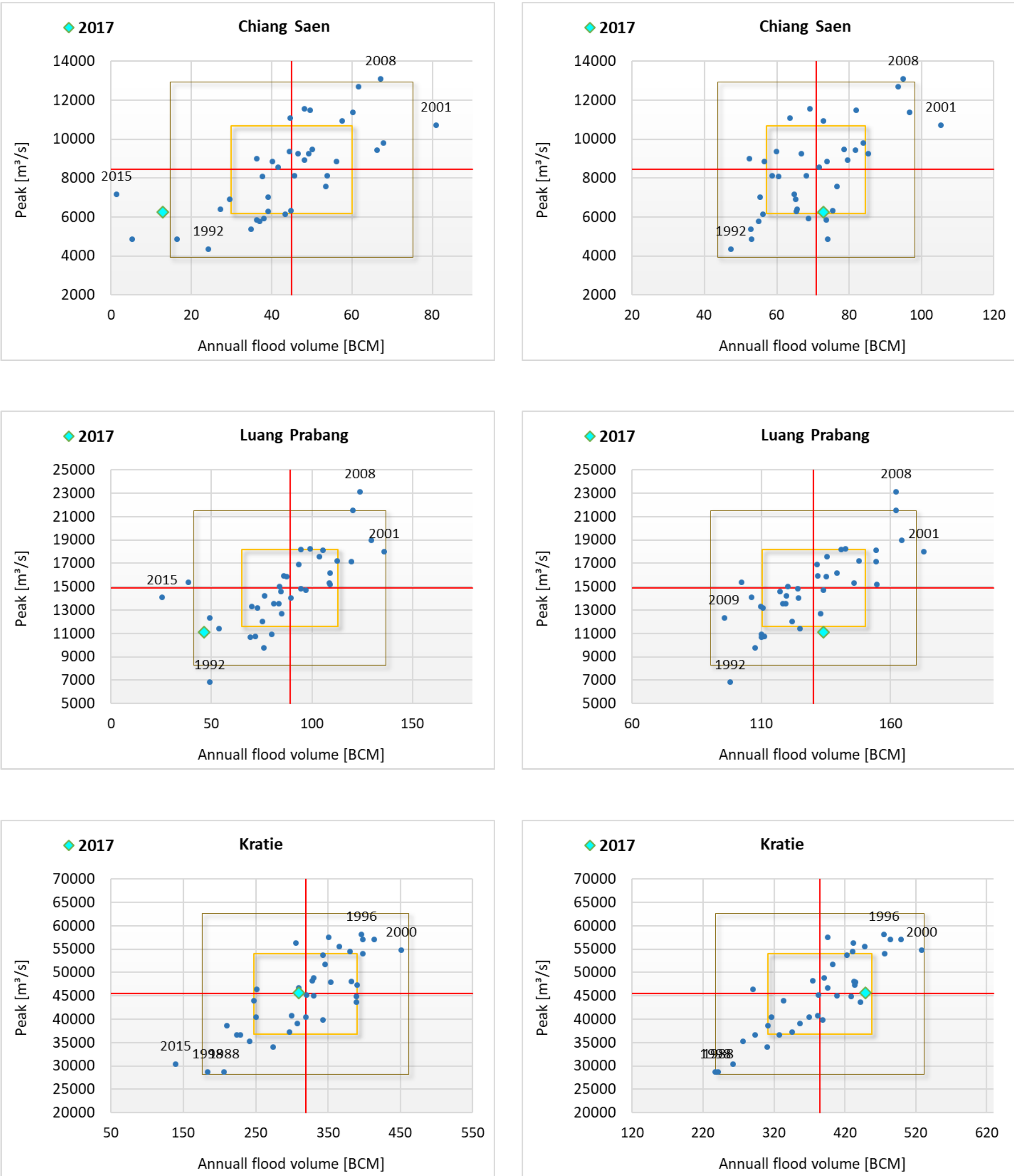


Figure 31: Flow and flood characteristics at selected stations 2017

- In 2017, Chiang Saen had both a very low flood volume and a low peak discharge. Luang Prabang is the last station with a rather low flood volume when considering baseflow. This is again an indicator of a change in the flow pattern.

With baseflow (=April) | Without baseflow



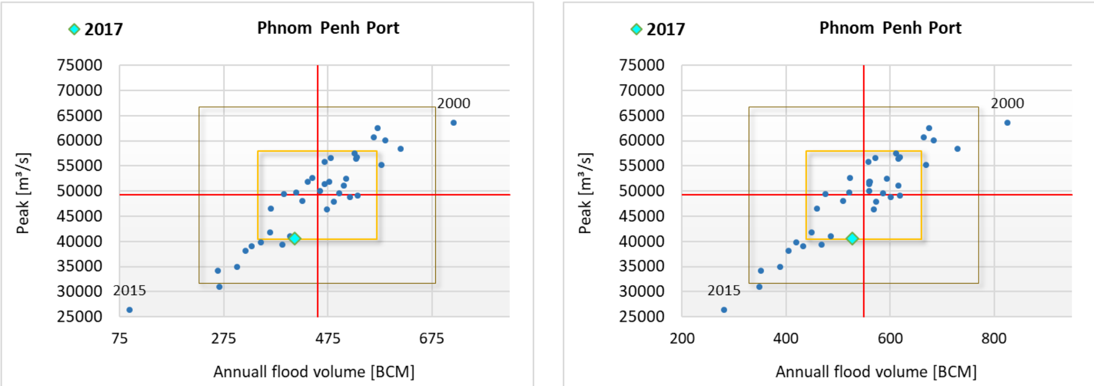


Figure 32: Flood volume/peak discharge relationship at selected stations 2017

The inner rectangle in the chart indicates derivation in the magnitude of the standard deviation for both peak discharge and annual flood volume. The outer rectangle simply doubles the standard deviation. Baseflow was simplified as the average flow in April and subtracted.

3.4 Regional flash floods 2017

In 2017, flash floods occurred during five events, namely:

Table 7: Flash flood events in 2017 (MRC, 2018)

9 July	Northern part of Viet Nam and Lao PDR, caused by low pressured
17 July	Northern provinces of Viet Nam, Lao PDR, and Cambodia caused by tropical storm TALAS
20-25 July	Lao DPR and Viet Nam caused by Tropical Depression and tropical storm SONCA
3 August	Northern part in Viet Nam caused by ITCZ
15 October	Lower Mekong Basin on 15 October 2017, caused by Tropical Depression

The event on 9 July brought heavy rain in the middle parts of the LMB, recorded from 3-10 July at Paksane (334.3 mm), Nakhon Phanom (247.5 mm), and Thakhek (279.6 mm). The information on flash flood risk areas indicated by the MRCFFG system on 9 July 2017 at 00:00 UTC was confirmed by the information published in the Lao PDR newspaper "Vientiane Times" and Viet Nam on 12 July 2017.

Between 10-17 July, tropical typhoon TALAS caused accumulated rainfall in the range of more than 200 mm at Nakhon Phanom (204 mm), Khong Chiam (257 mm), and Pakse (203 mm). The FFG reported high flash flood risks on 17 July 00:00 UTC for many districts in Viet Nam, Cambodia, and Lao PDR confirmed by local media.

The period 17-24 July 2017 brought moderate to heavy rain to the upper and middle parts of the LMB. The maximum accumulated rainfall was recorded at Paksane (211 mm) followed by Koh Khel (211 mm) and Stung Treng (205 mm). On 20 July, the FFG indicated high flash flood risks for districts in all four Member Countries with the highest risks along the border

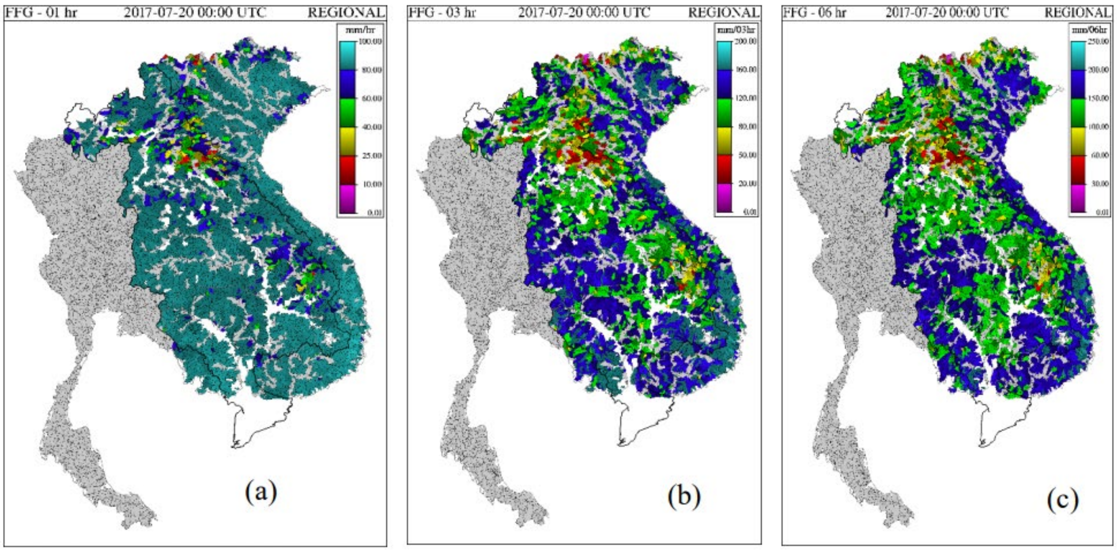


Figure 33: Flash flood rick areas detected by MRCFFGS on 20 July 2017 (a) FFG 01h, (b) FFG 03h and (c) FFG 06h (source: (MRC, 2018)

Unusually late in October, the LBM was influenced by a tropical depression from 9-6 October 2017, causing accumulated rainfall at Luang Prabang (120 mm), Neak Luong (120 mm), and Tan Chau (100 mm). Although the values were approximately 50% lower than during previous events in July and August, the high antecedent soil moisture gave rise to the issuance of high flash flood risks. However, no incidences were associated to this event.

The maximum daily precipitation observed in 2017 at 170 stations is illustrated in Figure 34.

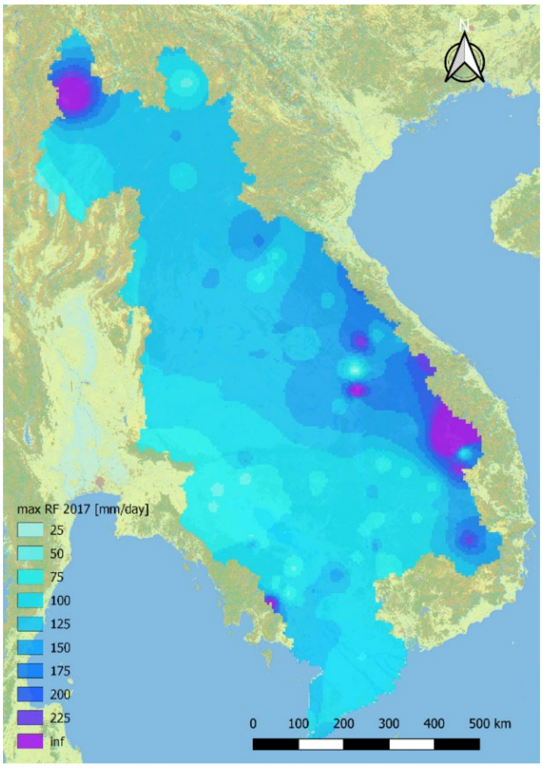
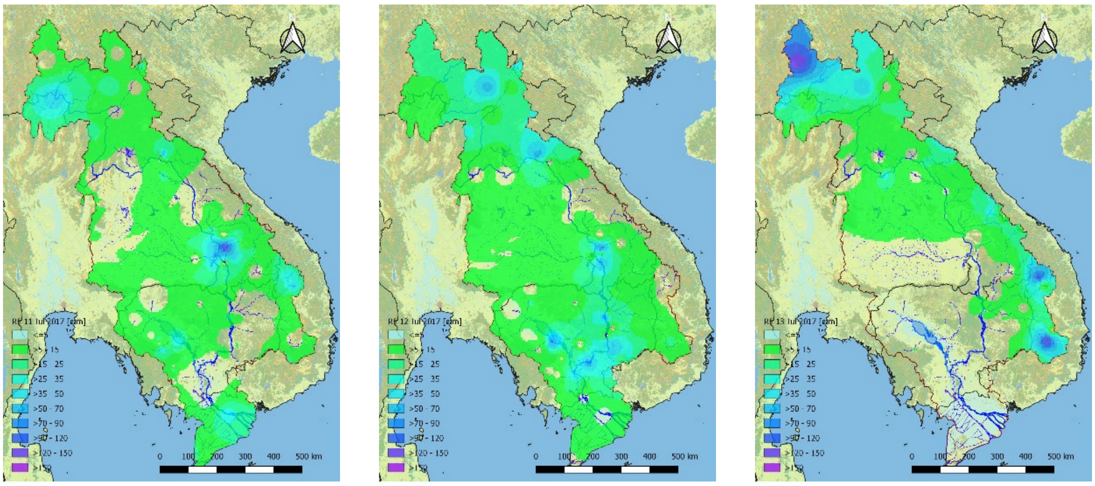


Figure 34: Maximum daily rainfall in the LMB in 2017

Following the incidences from the beginning to mid-July, the course of the rain that occurred from 11-19 July is illustrated below. It was the result of a tropical depression and typhoon Talas, and caused severe flash flood events with daily rainfall above 200 mm.



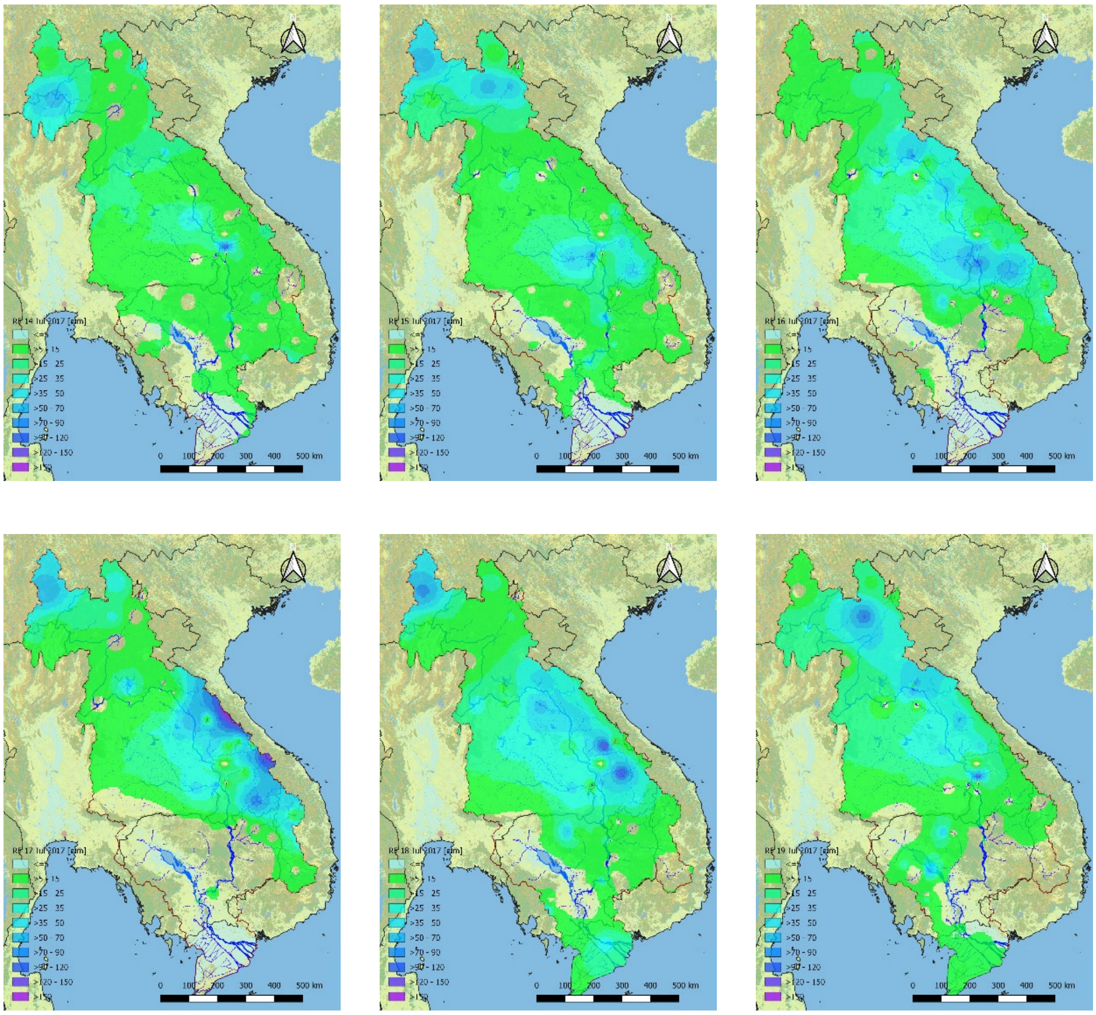


Figure 35: Rainfall as a result of Taifun *Talas* from 11-19 July 2017

All days with rain between 2006 and 2016 were sorted for each year separately and then maximum values were extracted from all years for each day 1 (highest) to 365 (lowest). For example, the day with the highest rainfall in each year obtains the index 1. The max value for index 1 out of the years 2006 to 2016 is then taken from all days with index 1. The second largest rainfall day obtains the index 2 and the max value is selected based on all days with index 2 and so on. Illustrated are the 140 days of highest precipitation from 2006 to 2016 and compared to 2017 at selected stations. If the red line, which represents 2017, lies above blue, daily rainfall intensity in 2017 is higher than the maximum recorded between 2006 to 2015.

This is the case for Mukdahan. This means that during the 2017, Mukdahan faced higher rainfall intensities for a period of 40 days than in the previous 40 years. Only the peak was not exceeded. All other stations did not exceed maximum conditions from 1980 to 2016.

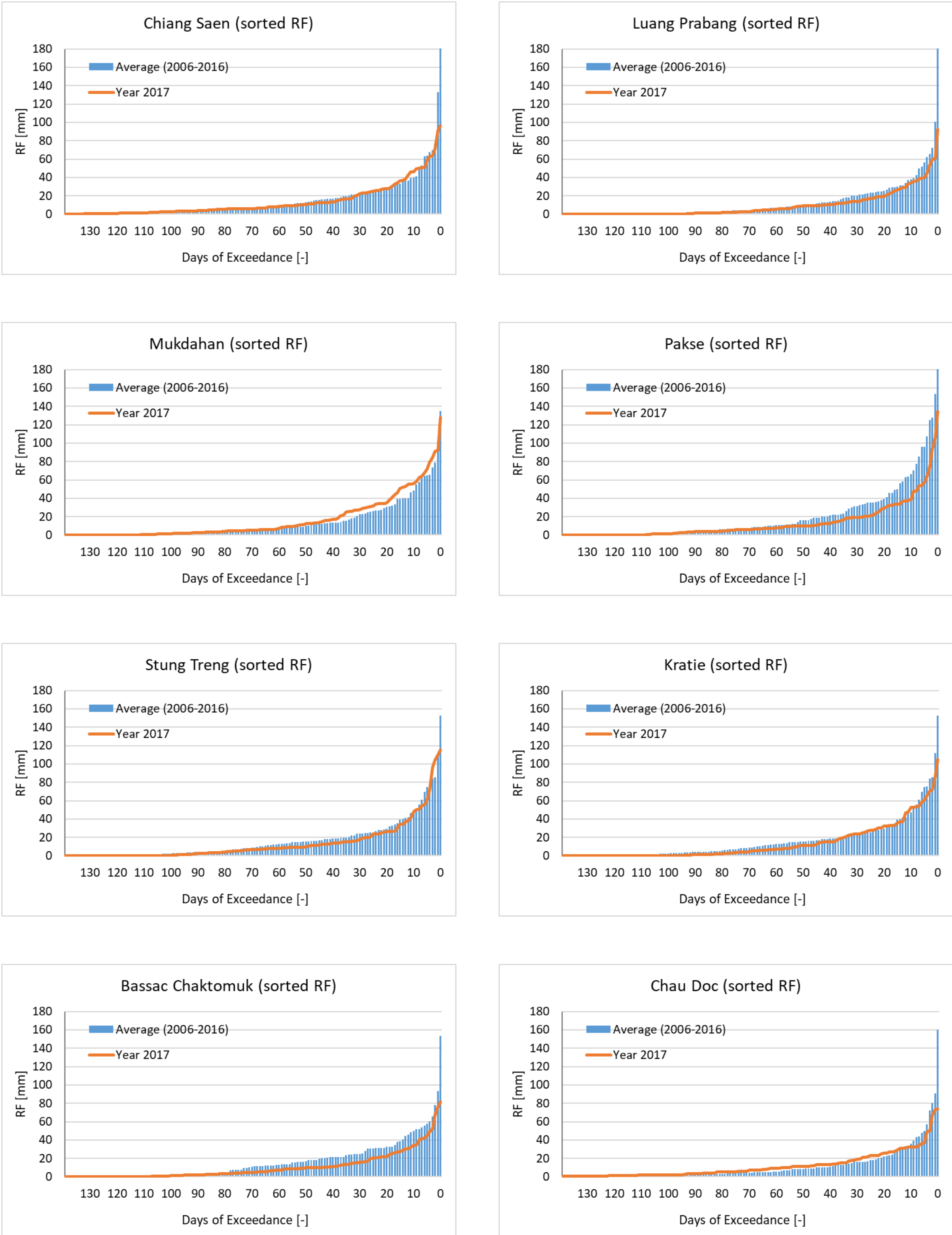


Figure 36: Rainfall intensities at selected stations 2017

3.5 Drought conditions in 2017

The anomaly of rainfall in 2017 is shown in Figure 37. Only stations with a maximum of 1 year of error data are selected. Apart from Pakse, where the previous four years show a deficit, all other stations indicate a surplus of rain compared to the average from 1980 to 2016.

The surplus varies and is largest at Mukdahan. The deficit at Pakse is only 50 mm or 2.5%. Summarizing the conditions of 2017 from the viewpoint of rain shortage, there is no indication of a lack of rainfall. However, this does not necessarily mean that no water shortage occurred at all. Firstly, the picture shows only a selection of the stations along the Mekong mainstream and secondly, no comparison between rainfall and water demand was made.

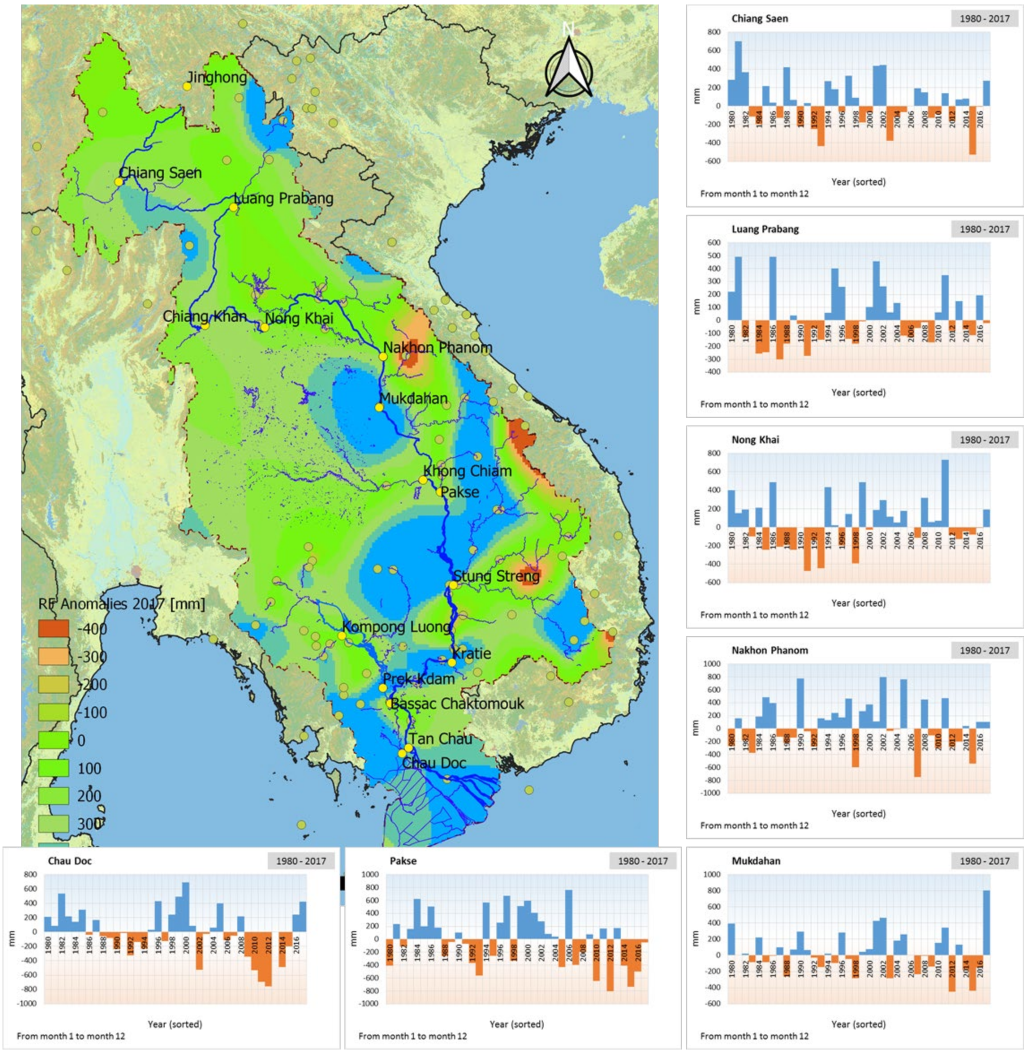
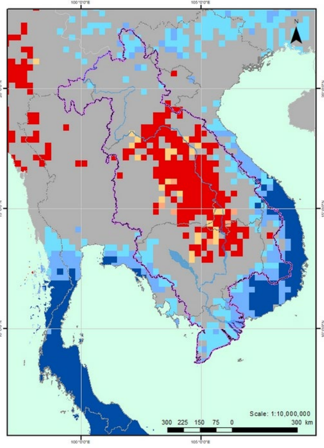


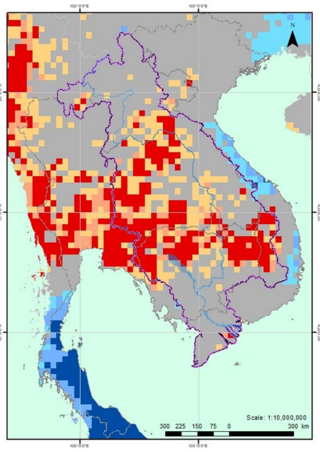
Figure 37: Rainfall anomalies 2017 derived from selected stations

Details of the year on a day-by-day basis are provided at the MRC drought monitoring and forecasting website (http://droughtforecast.mrcmekong.org/maps). One product shown on the website is the meteorological drought index SPI (Standardized Precipitation Index) with an aggregation period of one month. One month was chosen to avoid misleading information during the transition from dry to wet and wet to dry seasons (MRC, 2019), and to reflect rapid changes of conditions (see Figure 38).

Another index provided is the Combined Drought Index CDI. CDI is a combination of three indices: SMDI, SPI, and SRI, where SMDI is Soil Moisture Deficit Index and SRI is Standardized Runoff Index. CDI is calculated with different weights according to the importance of the conditions, where SMDI obtains a weight of 1.5 whereas SPI and SRI obtain 1, as the last two variables are similar in their behaviour in comparison to SMDI. It is a dimensionless index varying between -3 to 3 (see Figure 39). CDI is considered most relevant for depicting drought conditions as it combines meteorologically, hydrologically, and agriculturally relevant input.



25-01-2017



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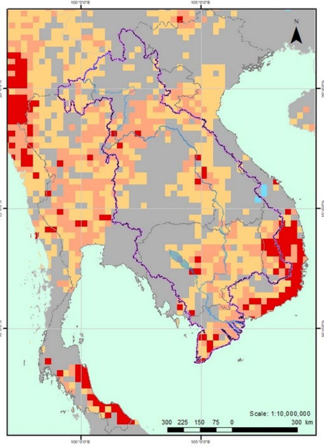

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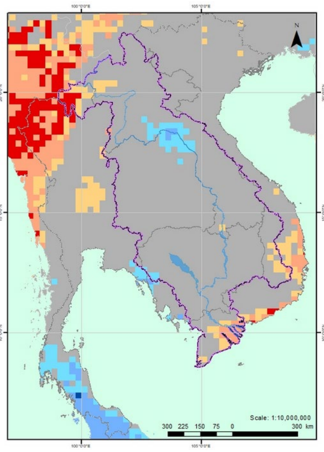

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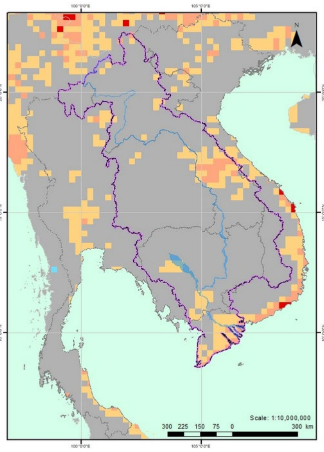

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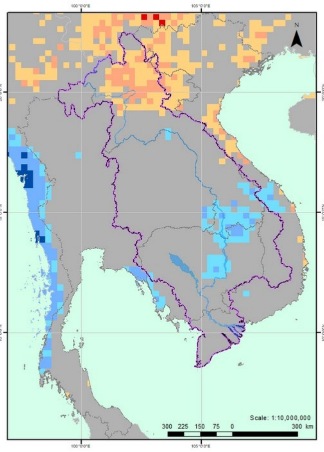

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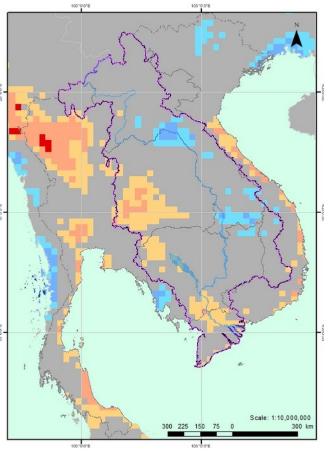
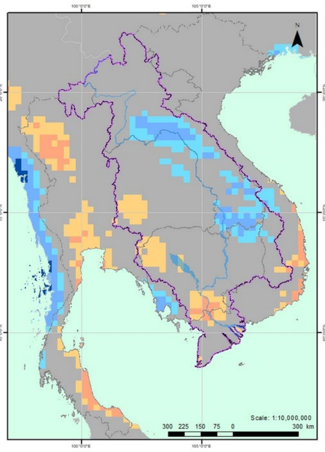
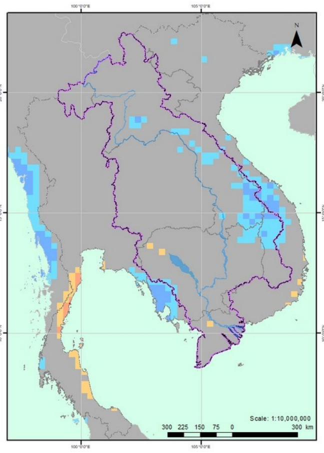
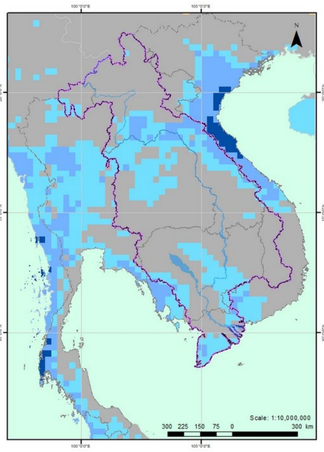
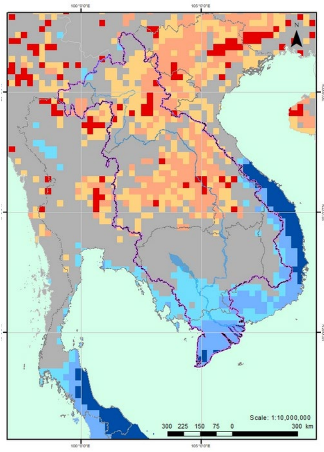
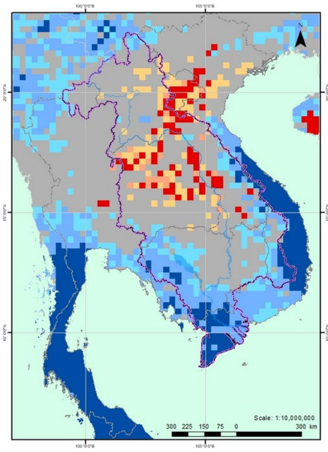




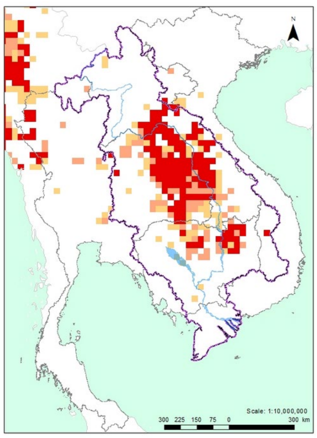
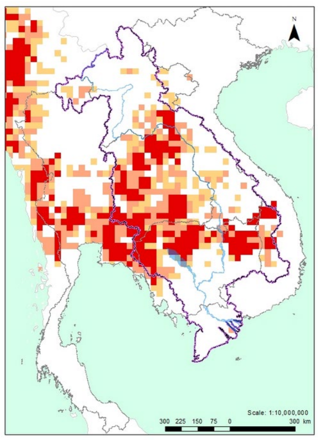
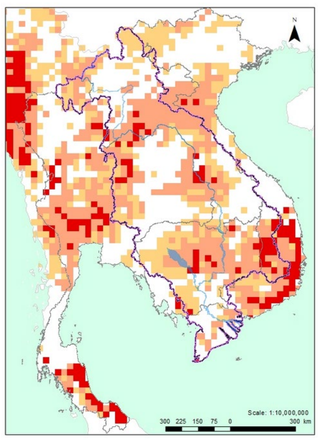


15-07-2017 15-08-2017 15-09-2017

15-10-2017 15-11-2017 15-12-2017

Figure 38: SPI index with 1 month aggregation for 2017

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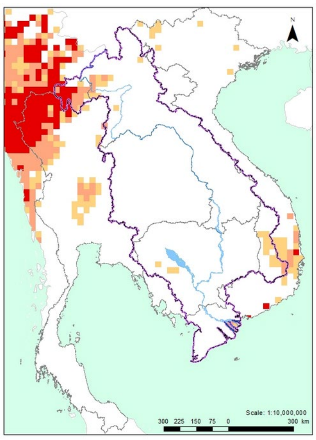
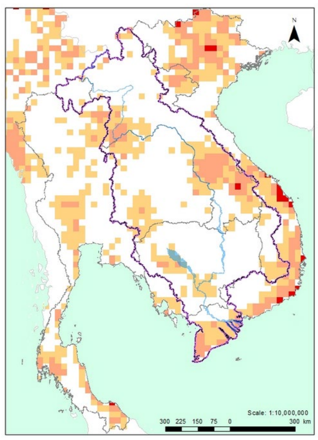
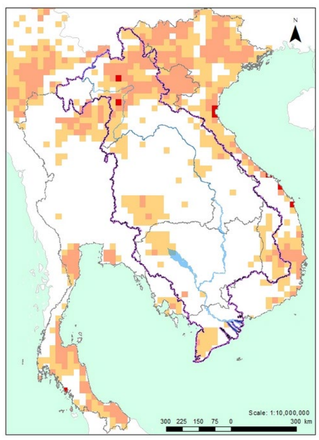

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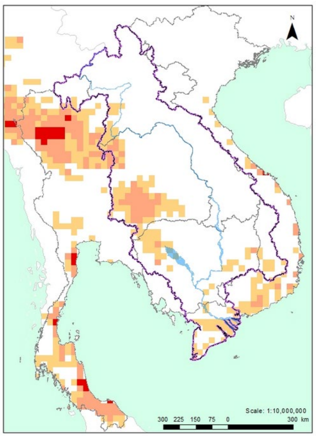

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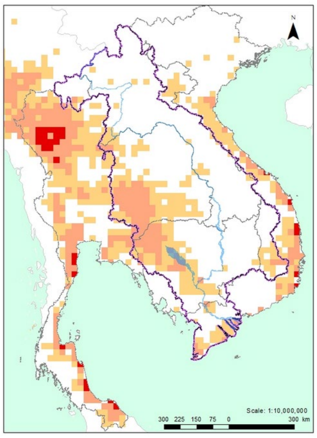

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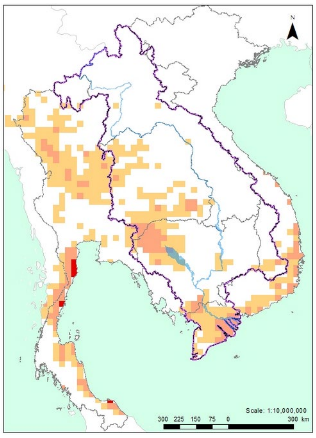

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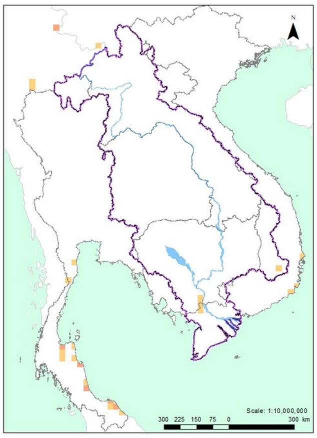

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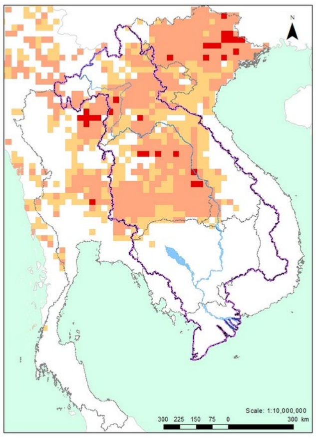

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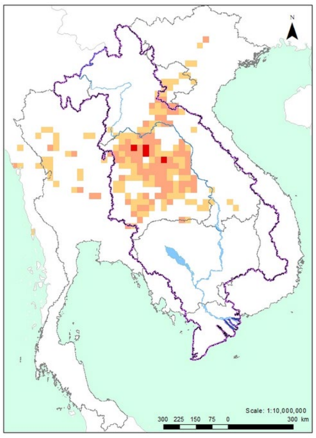

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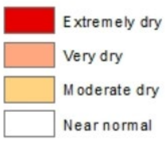
Figure 39: CDI index for 2017

SPI:

CDI:



The differences between SPI and CDI demonstrate the inertia and increased weight of soil moisture, and make sector-relevant evaluation visible. As such, CDI is not a stand-alone probabilistic representation but a combination of several variables to form an understandable set of conditions to represent the drought status.

If the CDI is low indicating dry conditions, it does not indicate anything about resulting impacts. If impacts from droughts need to be addressed in the future comparable to floods, it is necessary to assess water deficits and to know water demand.

5 COUNTRY REPORTS

5.1 Cambodia

5.1.1 Introduction

Cambodia faced a number of extreme hydrological events caused by the Mekong River. Exceptional floods occurred in 1978, 1996, 2000, 2001, 2002, 2011, and 2013, and extreme dry years were observed in 1988, 1998, 2010, 2015, and 2016. Although there is a risk of flooding, the population density along the banks of the Mekong River and around Tonle Sap Lake is significantly higher compared to other regions in the country. People living along the Mekong have adapted themselves to the rhythm of the Mekong floods.

In Cambodia, the traditional way of using floodwater for agriculture was the Colmatage canal system, which diverts water from major streams across the levees into the floodplain. These canals are manmade using natural remnants of the river branches. Modern Colmatage canals are equipped with control structures like gates upstream and downstream and designed in such a way to provide maximum spreading of silt. The gates provide control for flood protection (early flooding to allow proper maturation and harvesting) and prevent water from receding (when water in the mainstream start reducing) for dry season cropping. Dike systems were used to protect cities, towns, and agricultural land from flooding, and sometimes to create shallow reservoirs for dry season cropping and access roads.

5.1.2 Regional climate in 2017

In Cambodia, rainfall distribution is characterized by the topography of the country and can be subdivided into four regions: 1) the mountainous area in the north and southwest (Dangrek, Kravanh, Cardamon); 2) the highland plateau in the east; 3) the central lowland and flood plains of the Mekong; and 4) the coastal area in the southwest. The highest amount of rainfall occurs in the coastal area and the lowest in the lowland area.

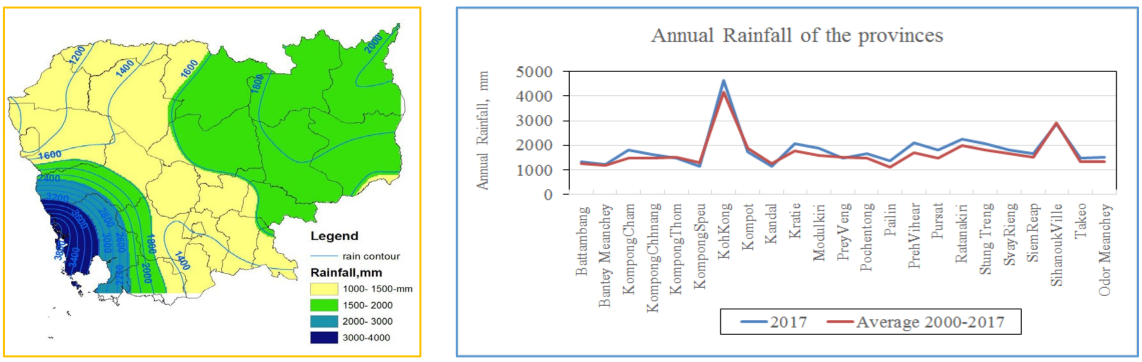


Figure 40: Annual rainfall in 2017 and average from 2000-2017, Cambodia

In 2017, the average cumulative rainfall in Cambodia was approximately 1830 mm, which is roughly 10% higher than the long-term average for 2000-2017. The lowest annual rainfall of

1137 mm was recorded in Kompong Speu and the highest with 4,637mm in Koh Kong Province.

Cambodia was affected by tropical storms and typhoons, namely Talas, Sonca, Doksuri, Damrey, and Tembin (see Figures 22 and 23).

5.1.3 Hydrological situation in 2017

Stung Treng, Kratie, Kompong Cham, Tboung Khmum, Phnom Penh, Svay Rieng, and Prey Veng provinces were most affected by river floods in 2017.

Table 8: Peak water levels in the Mekong River and tributaries in 2017, Cambodia

Name of Station	Cause	Warning Level (m)	Peak Water Level in 2017 (m) with date	Historic max. water level (m) with year
			(dd/mm)	
Mekong-Stung Treng	Mekong flood	10.70	10.68 (29/07)	12.19
Mekong-Kratie	Mekong flood	22.00	21.26 (30/07)	23.01
Mekong-Kompong Cham	Mekong flood	15.20	14.62 (01/08)	16.11
Bassac-Chaktomuk	Mekong flood	10.50	8.86 (02-23/08)	11.20
Mekong-Neak Luong	Mekong flood	7.50	6.36 (02/08)	8.12
Bassac-Koh Khel	Mekong flood	7.40	7.50 (01/08)	7.94
Tonlesap-Prek Kdam	Mekong flood	9.50	7.75 (28/09)	10.26

The peak water levels in 2017 were similar to the long-term average at Stung Treng, Kratie, and Kompong Cham. From the beginning of the rainy season to the middle of August 2017, observed water levels were higher than the long-term average, but below average during the receding phase.

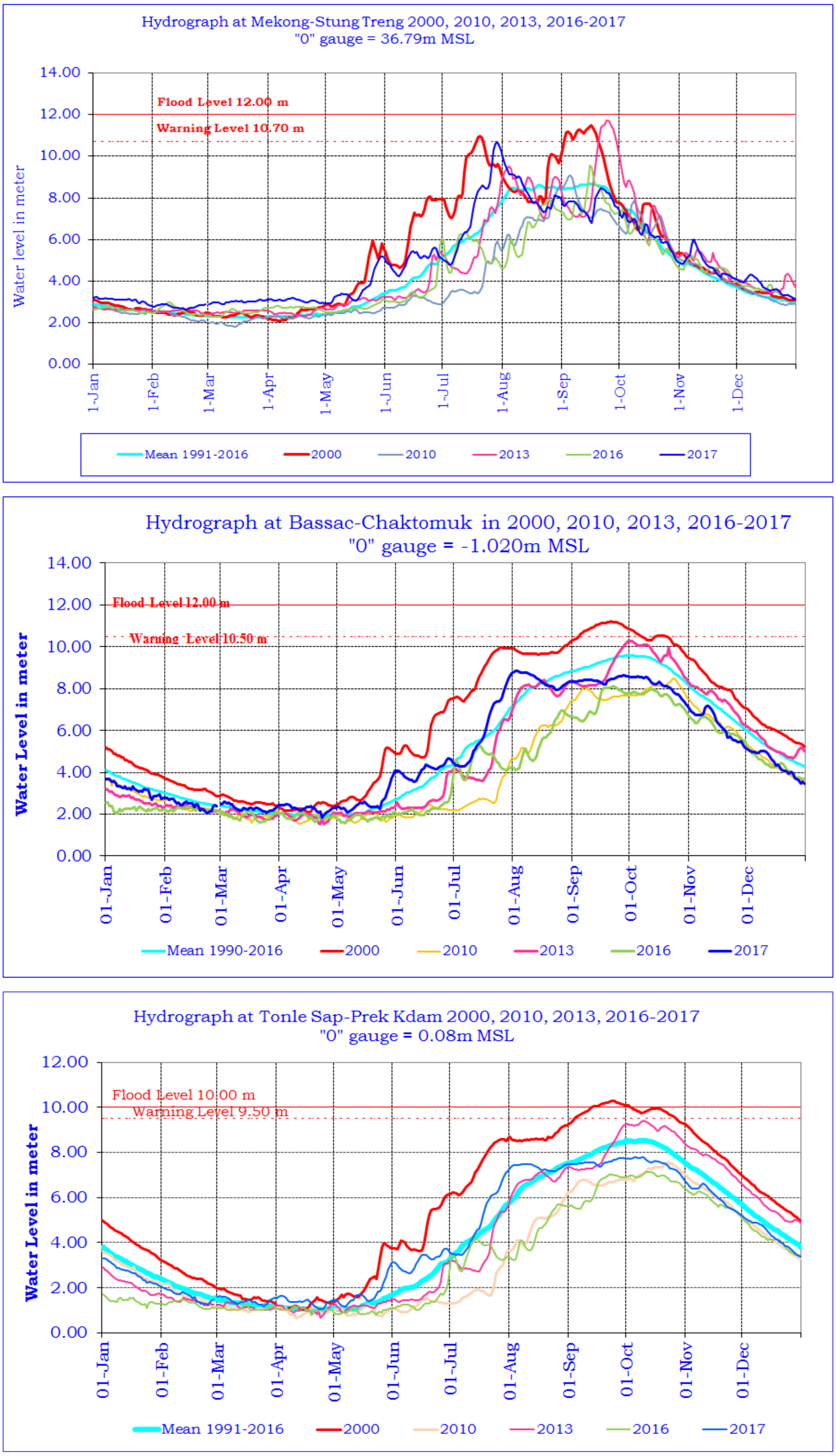


Figure 41: Hydrographs at Stung Treng, Chaktomuk and Prek Kdam

The rise of the water level of Tonle Sap Great Lake started about 2 weeks earlier than the long-term mean, which was likewise for the peak and the decline.

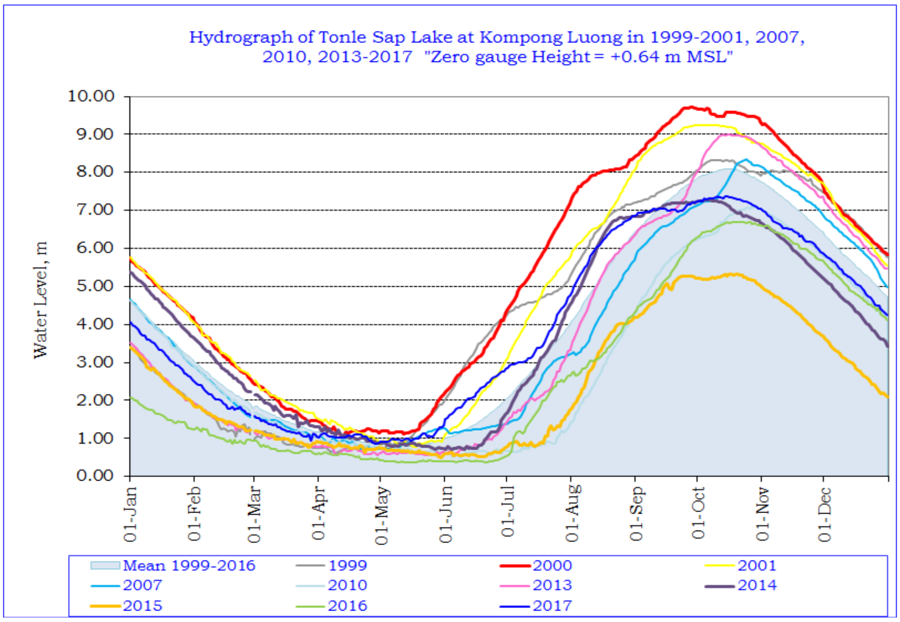


Figure 42: Hydrograph of Tonle Sap Great Lake at Kampong Luong

The provinces Preah Vihear, Udormeanchey, Banteaymeanchey, Kompong Thom, Kampot, Preah Sihanouk, Ratanakiri, Paillin, and Siem Reap reported flash floods.

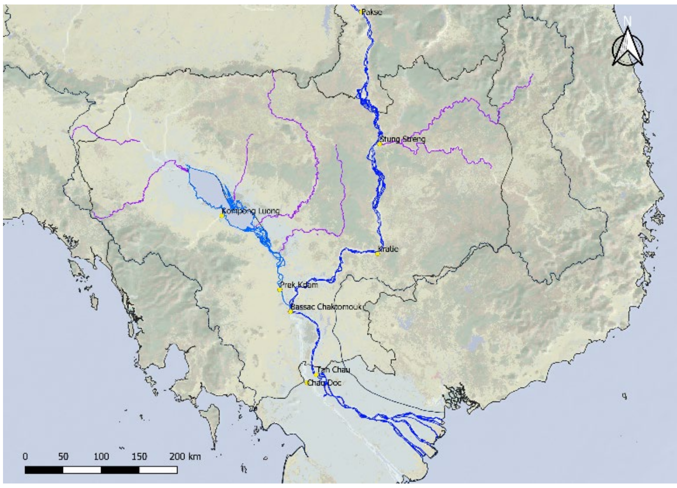


Figure 43: Rivers affected by flash floods in Cambodia

Drought was not an issue in 2017, although very high temperatures were reported in March and April in combination with below average rain. However, precipitation in May came as a release so that no damage was observed to agriculture.

5.1.4 Impact of flooding/drought 2017

The impacts of flooding increased due to sustained migration from rural to urban areas.

Table 9: Impacts of floods and droughts compiled for Cambodia from 1996 to 2017

Year	Disasters	Affected/ Damages
1996	Severe flood	In the 1996 floods, continuous heavy rainfall caused inundation affecting 1.3 million Cambodians with 600,000 hectares of crops and 50,000 homes damaged or destroyed; 13 provinces were affected.
1999	Flood and Typhoon	37,527 people in 10 provinces were affected, 17,732ha of rice crop and 491 houses were destroyed.
2000	Severe flood	3,448,629 people were affected, 768 houses were damaged and 347 deaths occurred.
2001	Severe flood	429,698 families, equivalent to 2,121,952 people were affected. People killed: 62 (70% were children); houses destroyed: 2,251
2002	Flood and Drought	Drought: People affected: 442,419 families (2,017,340 individuals) Flood: People affected: 1,439,964; 1,082 houses destroyed; deaths: 29
2009	Typhoon Ketsana	14 provinces affected, 43 deaths, 67 severely injured, destroyed homes and livelihoods of some 49,000 families or 180,000 people (the equivalent of 14%), and 80% of total land area.
2010	Flash flood	14 provinces affected, 22,746 families affected, 6,301 houses affected, 86 houses damaged, 11 deaths, 7 injured, 272 schools affected, affected nurseries: 77,629 ha and crop damage across the country was 6,942 ha
2011	Severe flood	18 provinces affected, 354,217 families affected, 268,631 houses affected, 1297 houses damaged, 250 deaths, 23 injured, 1,360 schools affected, 491 pagodas, 115 health centres, seeding 431,476 ha, crops 21,929 ha, national roads 956,638m, laterite roads 5,594,119 m, etc.
2012	Flash flood	7 provinces affected, 23,691 families affected, 22,863 houses affected, 2 houses damaged, 27 deaths, 122 schools affected, 7 pagodas, 4 health centres, seeding 57,432 ha, crops 3,585 ha, laterite roads 25,4287 m, etc.
2013	Severe flood	20 provinces affected, 377,354 families affected, 240,195 houses affected, 455 houses damaged, 168 deaths, 29 injured, 1,254 schools affected, 533 pagodas, 92 health centres, seeding 37,847 ha, crops 81,244 ha, national roads 440,572 m, laterite roads 3,569,779 m, etc.
2014	Flash flood	13 provinces affected, 165,516 families affected, 87,333 houses affected, 185 houses damaged, 49 deaths, 4 injured, 397 schools affected, 154 pagodas, 32 health centres, seeding 77,325 ha, crops 10,077 ha, national roads 96,036 m, laterite roads 973,249 m, etc.
2015	Flash flood/ Drought	7 provinces affected, 789 families affected, 6,963 houses affected, 7 houses damaged, 1 death, 1 injured, affected seeding 3,707 ha, crops 7,943 ha

Year	Disasters	Affected/ Damages
2016	Flash flood	16 provinces affected, 17,928 families, 413 houses, seeding 26,553 ha, crops 3,610 ha, national roads 2,422 m and 11 places, laterite roads 105,955 m
2017	Flood and flash flood	16 provinces affected, 55 districts and 194 Communities. 18,674 families affected, 1,734 families evacuated, 7 households damaged. Death toll up to 17. 104 schools affected, 12 pagodas and 1 hospital. 5,918 heads of livestock evacuated, 22,067 ha of rice cultivation affected and 3,456 ha damaged.

Figure 44: Continuous rainfall for 2 days on 2-3 October 2017 in Banteay Meanchey province, Cambodia

The National Committee for Disaster Management compiled the number of people affected by flooding and flash floods.

Table 10: Affected people due to flooding and flash floods in Cambodia 2017 (source: National Committee for Disaster Management)

Flooding		Flash floods	
Region	People affected	Region	People affected
Stung Treng	1113	Preah Vihear	2404
Kratie	2225	Udor Meanchey	776
Tboung Khmum	1354	Banteay Meanchey	1501
Kompong Cham	137	Kompong Thom	2144
Phnom Penh	42	Kampot	2365
Prey Veng	30	Preah Sihanouk	115
		Ratanakiri	200
		Paillin	72
		Siem Reap	4196
Total	4901	Total	13773

5.2 Lao PDR

5.2.1 Introduction

The climate in Lao PDR is dominated by the tropical monsoon. The rainy season starts usually mid-May and lasts until mid-October with heavy rainfall in July, August, and September. The annual rainfall is approximately 1960 mm/year ranging from 1400 mm in the north to 3500 mm in the south. The dry season spans November to April. The lowest temperature usually occurs in December to February (13 – 17°C), and the highest in April (35 – 38°C). Relative humidity ranges from 65-95%. In Lao PDR, flooding and drought are the main natural disasters. These two phenomena can be expected to occur every year.

5.2.2 Regional climate in 2017

Four tropical cyclones affected Lao PDR from 1 January to 31 October 2017. Typhoon Talas was the first tropical cyclone of 2017 passing over Lao PDR. Talas made landfall in Central Vietnam near the city of Vinh and kept moving crossing Xienkhang, Xaysomboun, and Bolikhamxay Provinces in Lao PDR in the early morning of 17 July 2017. Talas was downgraded to a tropical depression while passing the north-western part of Lao PDR on 17-18 July. Cumulative rainfall within four days totalled more than 160 mm in Xiengkhuang and Thakek provinces.

Sonca was the second Tropical Cyclone of the year. Landfall was again near the city of Vinh in the evening of 25 July. Sonca affected Khammoune and Savannakhet provinces and brought more than 300 mm in four days in the districts of Paksong and Pakse.

Doksuri, the third cyclone in 2017, passed through Lao PDR on 16 September, followed by the fourth event, which reached the central part of Lao PDR on 11 October 2017.

5.2.3 Hydrological situation in 2017

In 2017, all water level observation stations along the Mekong River were below warning levels, except for Pakse.

Table 11: Peak water levels on the Mekong River in 2017, Lao PDR

No	Name of station	Warning Level (m)	Emergency Level (m)	Peak Water Level in 2017 (m)
1	Mekong at Houasai	16.50	17.50	
2	Mekong at Pakbeng	29.00	30.00	
3	Mekong at Luangprabang	17.50	18.50	12.98 (19 Aug 2017)
4	Mekong at Paklay	16.00	15.00	

No	Name of station	Warning Level (m)	Emergency Level (m)	Peak Water Level in 2017 (m)
5	Mekong at Vientiane	11.50	12.50	9.02 (18 Sep 2017)
6	Mekong at Paksane	13.50	14.50	11.45 (18 Sep 2017)
7	Mekong at Thakhek	13.00	14.00	11.10 (30 Aug 2017)
8	Mekong at Savannakhet	12.00	13.00	10.30 (31 Jul 2017)
9	Mekong at Pakse	11.00	12.00	11.54 (27 Jul 2017)

Table 12: Peak water levels for Tributaries in 2017, Lao PDR

No	Name of Station	Warning Level (m)	Dangerous Level (m)	Peak Water Level in 2017 (m)
1	Nam Ou at M. Ngoy	16.50	17.50	9.80 (16 Aug 2017)
2	Nam Khan at Xiengngeun	11.00	10.00	
3	Nam Song at Vangvieng	3.50	4.50	3.76 (9 Jul 2017)
4	Nam Lik at Hineheup	14.00	15.00	
5	Nam Sane at Bolikhane	7.00	8.00	8.72 (7 Jul 2017)
6	Nam Ngiep at M. Mai	11.00	12.00	8.80 (18 Jul 2017)
7	Nam Ngum at Thalat	16.00	17.00	
8	Nam Ngum at Pakkagnoung	11.00	12.00	6.56 (19 Jul 2017)
9	Nam Ngum at Veunekham	12.00	13.00	
10	Nam Kading at Ban Phonesi	13.75	14.75	12.03 (6 Aug 2017)
11	Sebangfai at Mahaxay	14.00	15.00	14.89 (20 Jul 2017)
12	Sebangfai at M.Sebangfai	17.50	18.50	19.54 (20 Sep 2017)
14	Sechamphone at Kengkok	7.50	8.50	
15	Sebanghieng at Kengdone	14.00	15.00	
16	Sedone at Slavane	10.50	11.50	8.67 (27 Jul 2017)

No	Name of Station	Warning Level (m)	Dangerous Level (m)	Peak Water Level in 2017 (m)
17	Sedone at Khongsedone	12.30	13.30	13.10 (27 Jul 2017)
18	Sekong at Sekong	16.00	17.00	
19	Sekong at Attapeu	15.00	16.00	13.45 (27 July 2017)

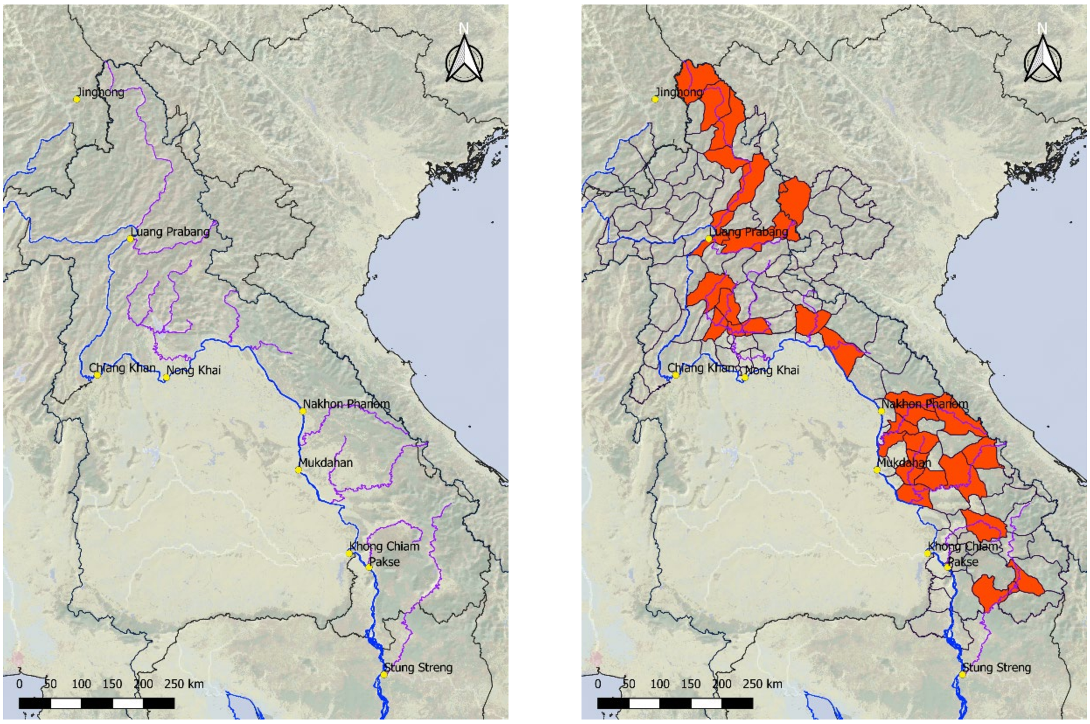


Figure 45: Mainstream and Tributaries, and provinces affected by flooding and flash floods in Lao PDR

5.2.4 Impact of flooding/drought 2017

In March 2017, a local hailstorm caused severe damage in some areas of north-western and central parts of Lao PDR.

Local Storm in Vientiane (17 March 2017)

Hail Storm in Muang Phonthong, Luangprabang (17 March 2017)

Hail Storm in Vientiane Province (16 March 2017)

In May 2017, a local storm caused flash floods in Muang Kenethao, Xaiyabouly Province. In July 2017, heavy rainfall triggered landslides causing severe damage in northern and central provinces. In total, 12 people were killed due to landslides and flash floods from July to September.

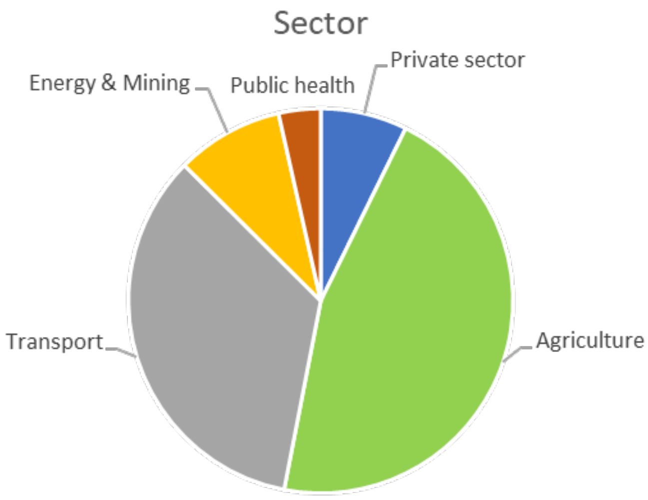


Figure 46: Distribution of costs due to floods and flash floods in Lao PDR

The 15 provinces affected were: Phongsaly, Luangnamtha, Oudomxay. Huaophane, Laungprabang, Xayabouly, Xiengkhuang, Vientiane Capital, Bolikhamxay, Khammuane, Savannakhet, Slavane, Campasack, Sekong, and Attapeu. This included 60 districts, 878 villages, 48,793 families, 249,760 people, and 10 fatal casualties. Total costs are estimated to run up to 4,330,187,000 Lao Kips. The agricultural sector was affected causing estimated costs of 27,197,300,334 Lao kips. Some 289 km of roads and five bridges were destroyed or severely damaged with costs of more 20,433,137,056 Lao Kips. The energy and mining sector had to face costs of 5,361,484,107 Lao Kips. Public health and education suffered losses of 2,098,631,152 Lao Kips or approximately USD 236,461,119.

5.3 Thailand

5.3.1 Introduction

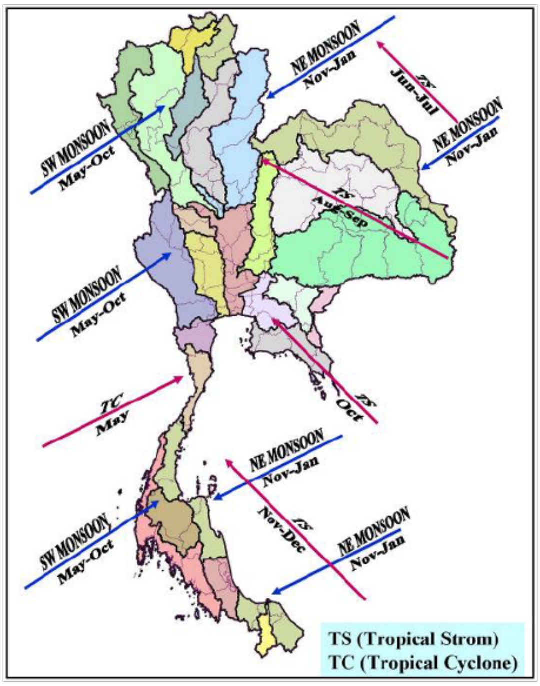
Thailand is located in the tropical area between latitudes 5o 37′ N to 20o 27′ N and longitudes 97o 22′ E to 105o 37′ E. The boundaries of Thailand with adjacent areas are: North – Myanmar and Laos; East – Laos, Cambodia and the Gulf of Thailand; South – Malaysia; West – Myanmar and the Andaman Sea. There are two regions that contribute to the LMB. The Norther part called 2T region, consisting of Chiang Rai Province and the North-Eastern part, called 3T&5T MRC-Sub basins.

(a) Location of Thailand

(b) Region of Thailand and BDP sub area

Figure 47: Thailand's sub-basins contributing to the LMB

Weather conditions in Thailand are dominated by monsoon with several major monsoon tracks indicated in Figure 48.



Source: *Thai Meteorological Department, H.Tipaporn (2017)*

Figure 48: General tracks of monsoon affecting Thailand

5.3.2 Regional climate in 2017

In 2017, 11 storms affected the country of which eight indirectly affected Thailand by low-pressure and rainfall, and three reached or moved into Thailand. Talas occurred mid-July and hit Nan province. Two weeks later, typhoon Sonca reached Nakhon Phanom Province. Doksuri, the third typhoon, arrived mid-September and struck Bueng Kan and Nan provinces.

Rainfall in 2017 can be described as wet, that is, the average annual rainfall of Thailand was 27% higher than the average annual value and was the highest in the period for 67 years (1951-2017).

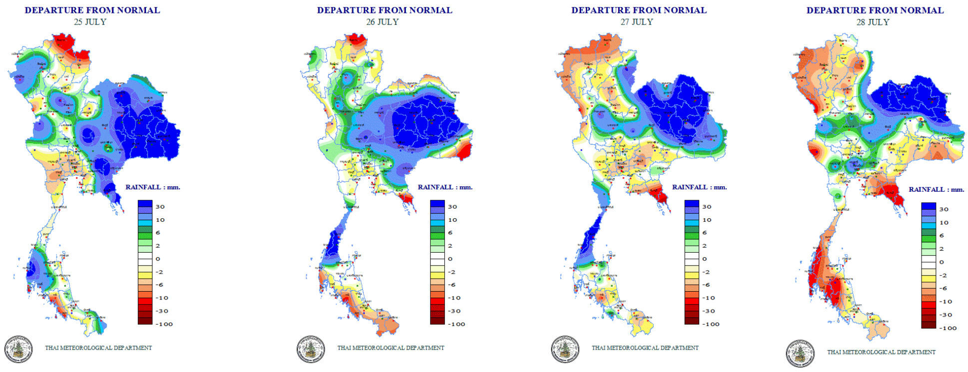
Typhoon Talas entered Thailand's territory on 17 July and brought widespread rain in northern parts of the country. The maximum daily rainfall of 179 mm was measured at Mae Sruai in Chiang Rai Province on 17 July. Thirty-two rainfall stations reported rainfall between 100 to 200 mm covering 8 provinces.

The second significant flood event in July was formed due to storm Sonca during 24-31 July 2017. This time, heavy rainfall hit the north-eastern regions. The short time between the occurrence of Talas and the arrival of Sonca brought about an unprecedented situation in some provinces. The aftermath of Talas had yet to subside when Sonca brought new rainfall so that the second event met saturated soil conditions leading to high runoff.

The third major events of 2017 occurred in the middle of September due to typhoon Doksuri between 14-19 September causing flooding in the lower parts of the North and North-eastern regions. The heaviest daily rainfall observed was 178 mm at Wang Chin in Phare Province on 16 September. Maximum daily rainfall in the Kok River Basin was about 162 mm measured at

Mae Fa Luang in Chiang Rai Province on 16 September. The Northern part of Thailand reported daily rainfall on 16 September from 100-1800 mm at 16 rainfall stations covering 5 provinces.

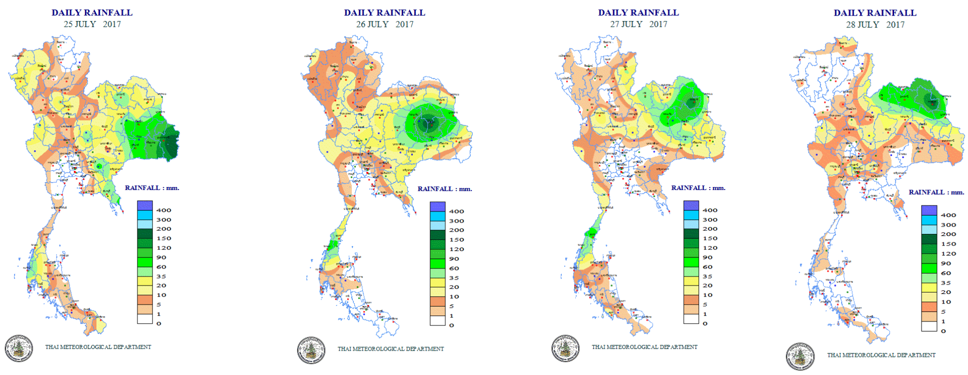
Large amounts of rain occurred in the North-eastern part of Thailand, especially in Sakon Nakhon Province, from 24-31 July 2017. The daily rainfall map is shown in



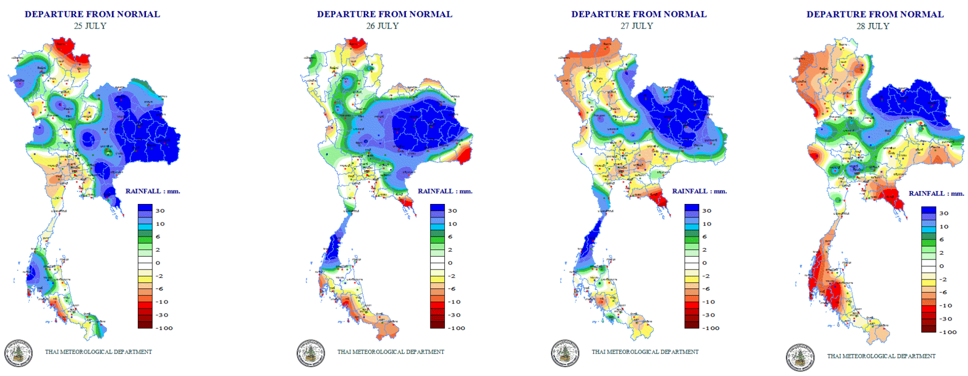
25 Jul. 2017 | 26 Jul. 2017 | 27 Jul. 2017 | 28 Jul. 2017

Source: Thai Meteorological Department (TMD)

Figure 49.



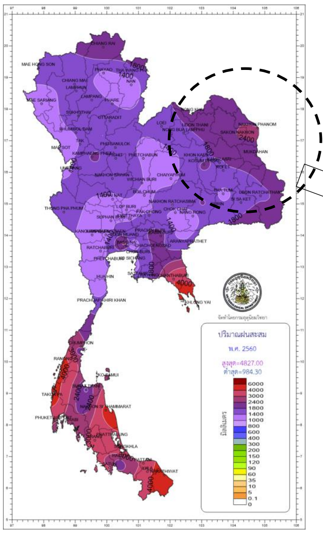
25 Jul. 2017 | 26 Jul. 2017 | 27 Jul. 2017 | 28 Jul. 2017



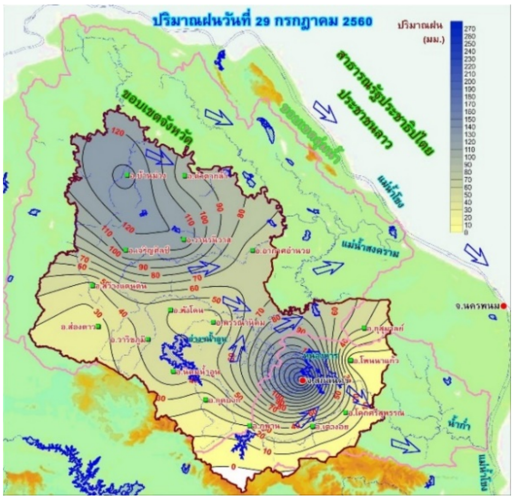
25 Jul. 2017 | 26 Jul. 2017 | 27 Jul. 2017 | 28 Jul. 2017

Source: Thai Meteorological Department (TMD)

Figure 49: Daily rainfall from 25-28 July 2017, Thailand



Annual Rainfall in 2017



Daily rainfall map on 29 July 2017 over Sakon Nakhon

Source: Thai Meteorological Department

Figure 50: Annual Rainfall in 2017 and daily rainfall in Sakon Nakhon Province, Thailand

2017 was an exceptional year for rainfall. The year showed a very similar amount of rain to 2011. In 2011, the resulting flooding caused one of the largest ever recorded flood-induced losses worldwide. Flood problems in 2017, however, were comparatively low.

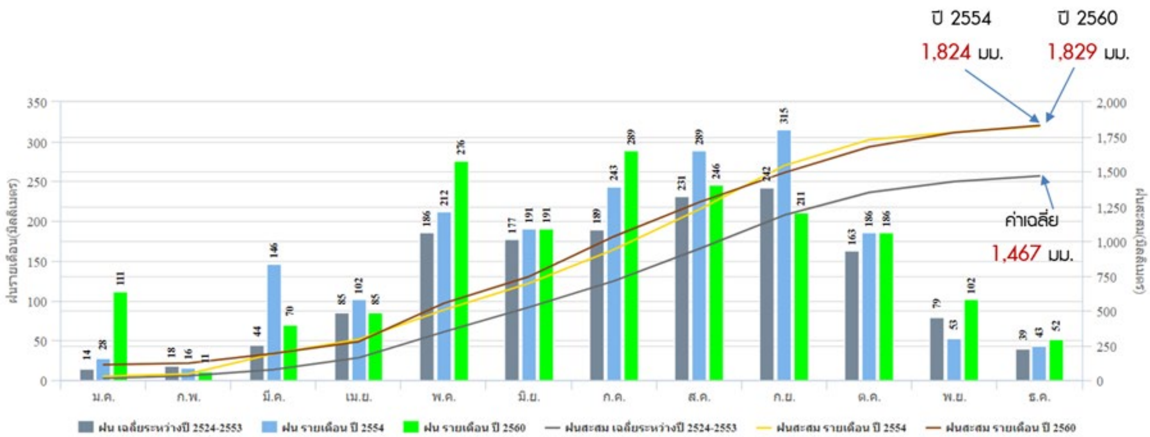
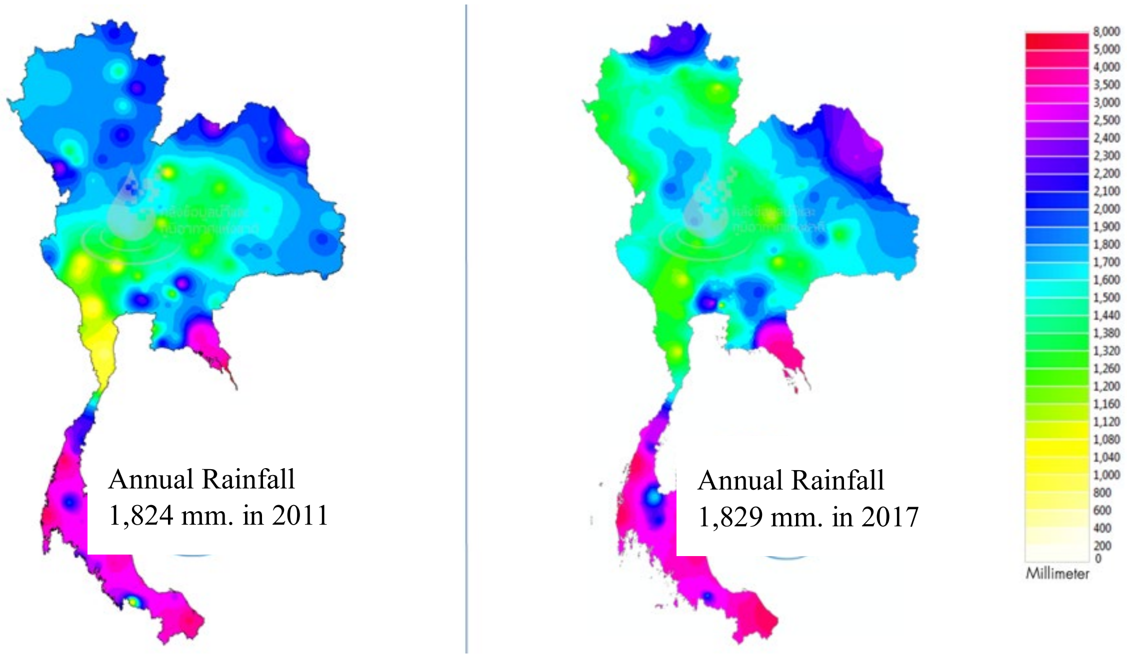


Figure 51: Cumulative rainfall 2017 compared with 2011, Thailand

In 2017, the average rainfall for the whole country was about 1,829 mm. For 2011, it reached 1,824 mm. As can be seen below, the affected regions differ.



Source: *www.thaiwater.net*

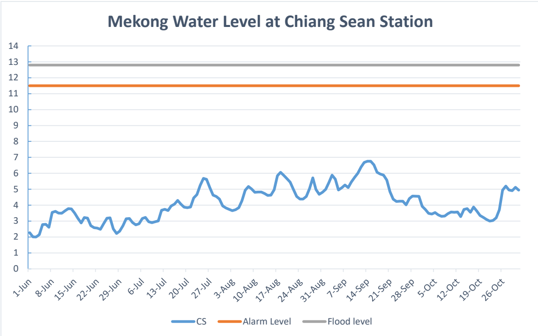
Figure 52: Spatial annual rainfall distribution 2017 and 2011, Thailand

5.3.3 Hydrological situation in 2017

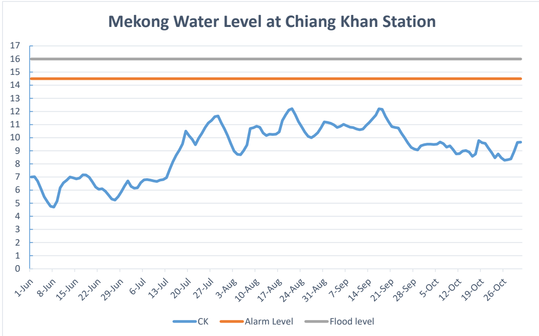
Thailand has six key monitoring stations on the Mekong mainstream operated by DWR. In 2017, water levels exceeding alarm levels occurred along the Mekong only at Khong Chiam.

Table 13: Peak water levels on the Mekong River and tributaries exceeding warning levels in 2017

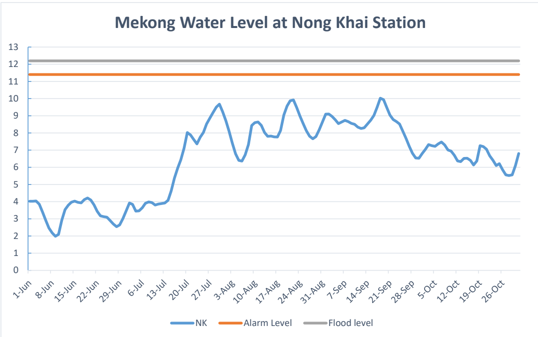
Name of Station	River	Warning Level (m)	Peak Water Level in 2017 (m) with date	Historic max. water level (m) with year
1.Chiang Sean	Mekong	11.50	6.76 m (15/09/2017)	14.00 m (03/09/1966)
2.Chiang Khan	Mekong	14.50	12.16 m (18/09/2017)	18.09 m (03/09/1966)
3.Nong Khai	Mekong	11.40	9.94 m (19/09/2017)	14.18 m (10/09/1966)
4.Nakhon Phanom	Mekong	11.50	10.05 m (01/08/2017)	13.30 m (19/08/1978)
5.Mukdaharn	Mekong	12.00	10.57 m (01/08/2017)	14.22 m (19/08/1978)
6.Khong Chiam	Mekong	13.50	13.50 m (30/07/2017)	17.77 m (19/08/1978)



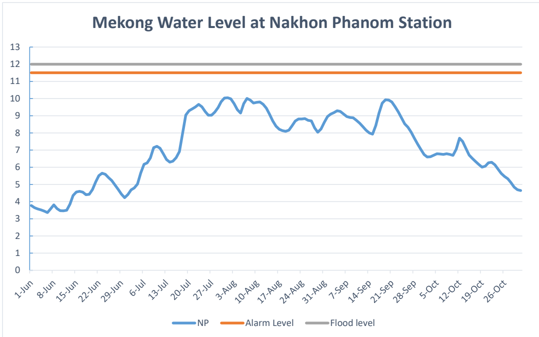
1.Chiang Sean



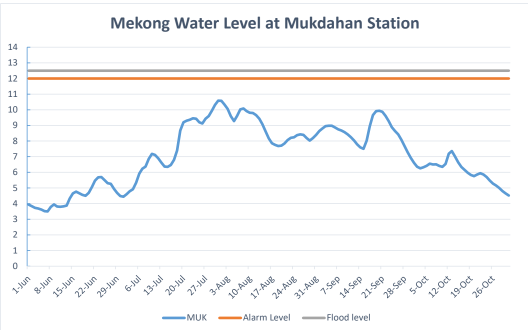
2.Chiang Khan



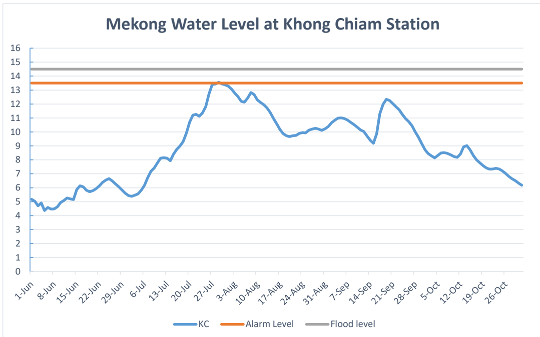
3.Nong Khai



4.Nakhon Phanom



5.Mukdaharn

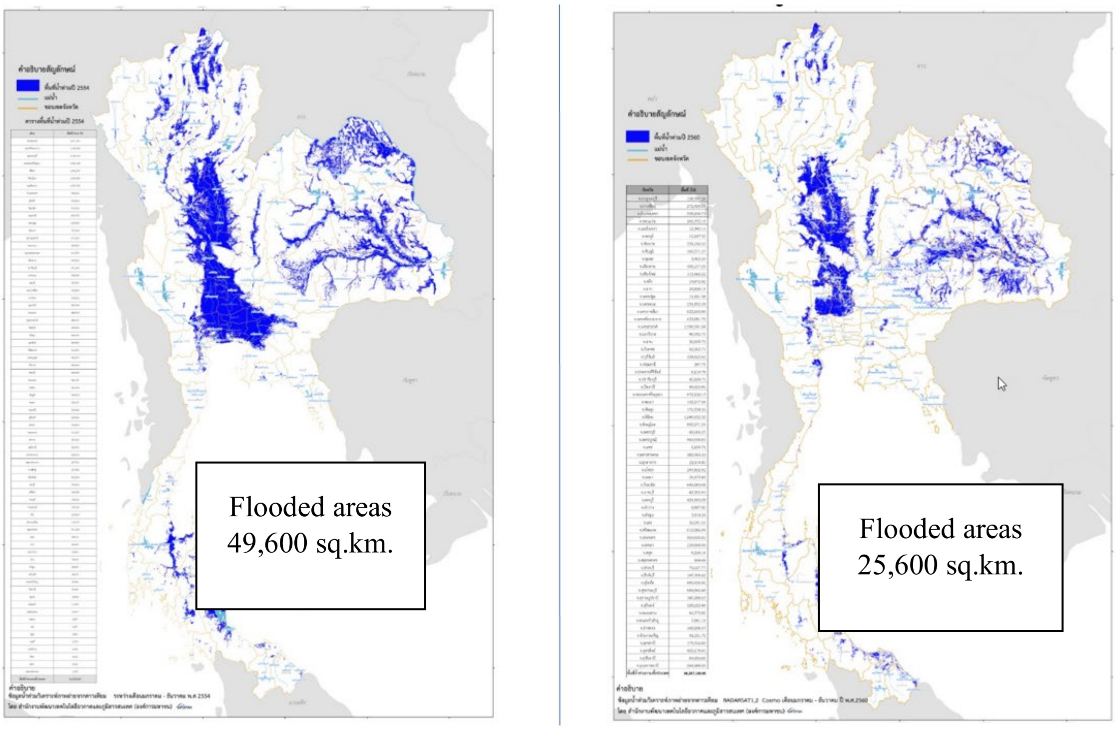


6.Khong Chiam

Source: *Department of Water Resources (DWR)*

Figure 53: Water levels in 2017 with alarm and flood levels at key stations on the Mekong mainstream, Thailand

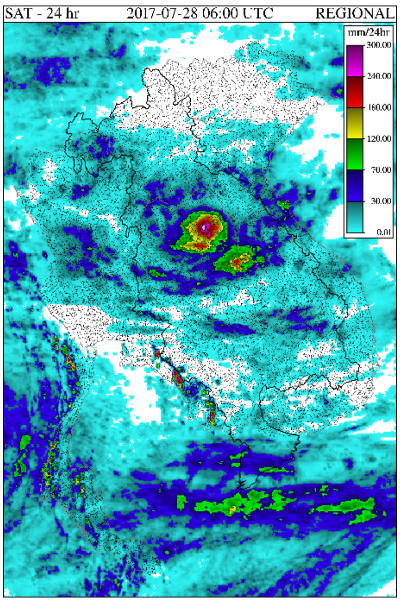
Despite 2011 and 2017 having similar amounts of rainfall, the resulting effects were different. 2011 brought flood problems in the central region of Thailand because of large flow volumes in 4 rivers, namely: Ping, Wang, Yom, and Nan, all of which drain into the Chao Phraya River. This region is a large lowland and a plain area, so it is difficult to drain abundant water with a tidally affected river like the Chao Praya. 2017 differed in that flood affected rivers drained into the Mekong River at a much higher capacity.



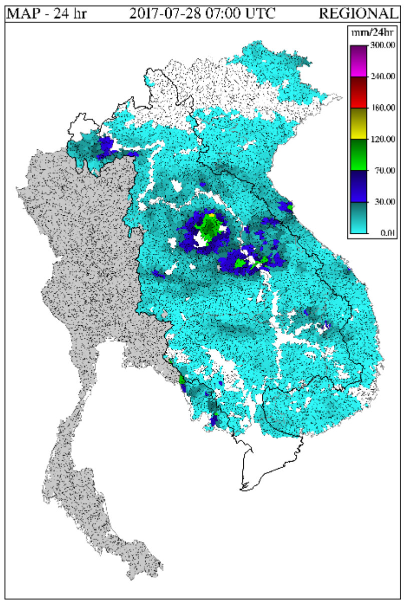
Source: *www.thaiwater.net*

Figure 54: Inundated areas in 2011 and 2017, Thailand

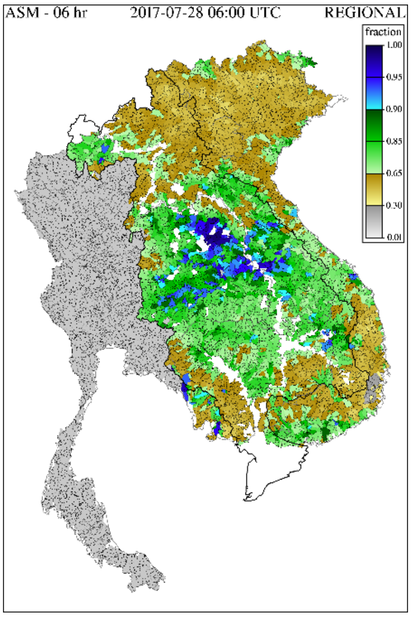
The MRC-RFDMC runs the Flash Flood Guidance (FFG) information system and publishes flash flood warnings for the next 1, 3, and 6 hours covering the entire LMB. The situation at the end of September is reviewed by means of Satellite Rainfall Estimates (SRE) compared with soil moisture conditions and the results of the FFG.



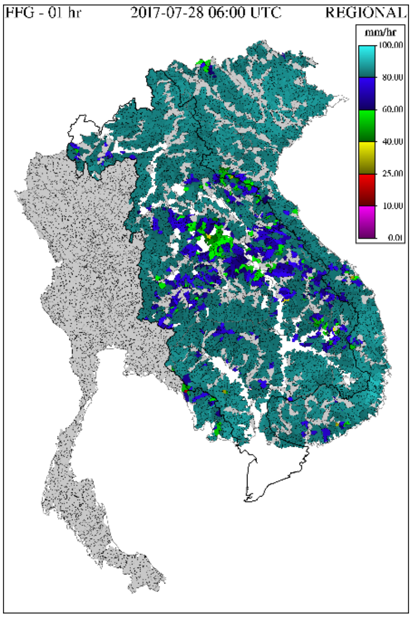
Satellite Rainfall Estimate on 28 July 2017



Mean Arial Precipitation on 28 July 2017



Average Soil Moisture on 28 July 2017



FFG at 01 hour on 28 July 2017

Source: *Mekong River Commission webpages*

Figure 55: Rainfall, soil moisture and FFG results from MRC-FFGS on 28 July 2017

The impact of Sonca is visible in all data sources. Figure 55 shows a good match between high soil moisture conditions in combination with high rain intensities leading to large runoff volumes.

In 2017, the onset of the monsoon came late but did not cause severe drought problems except for Sra Keo Province. The vulnerability to droughts is high in Thailand as can be seen from previous prolonged low rainfall periods in 2005, 2008, and 2016. As such, the Royal Thai Government has launched various water saving approaches to ensure that water reservoirs can satisfy the countries' water demand until the end of the dry season.

5.3.4 Impact of flooding/drought 2017

One of the hardest hit provinces was Sakon Nakhon. The pictures below were taken between 24-31 July.

Flood area in Nan Province

Flood area in Chiang Mai Province

Source: C. Thodsapol (2019)

Figure 56: Flooding in Sakon Nakhon Province, Thailand, in July 2017 cause by tropical storm Sonca

Floods in 2017 affected 21,186 villages. There were more than 602,213 families affected and 55 people were killed. Moreover, infrastructure, such as roads, bridges, drainage systems, buildings, schools, and temples were damaged. Preliminary costs were estimated at 803.23 Million Baht (26.77 Million USD).

Even though 2017 brought sufficient water on average, a few drought problems arose in Sra Keo Province. The Department of Disaster Prevention and Mitigation (DDMP) recorded about 10,300 ha of paddy fields as adversely effected by drought in the province. The number of people affected was estimated at 12,591 households, and the value of damages was given at 2.45 million USD.

5.4 Viet Nam

5.4.1 Introduction

Vietnam's climate can be divided into a tropical and a temperate zone. It is characterized by strong monsoon influences, a high rate of rainfall and high humidity. Regions located near the tropics and in the mountainous regions have a slightly cooler, more temperate climate.

Generally, the Mekong Delta and the Central Highlands of Viet Nam have two seasons as indicated in Figure 57.

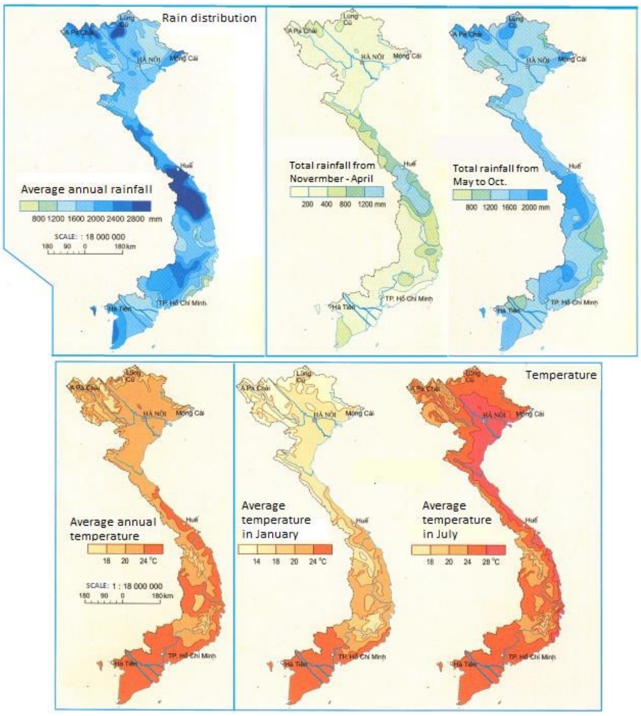
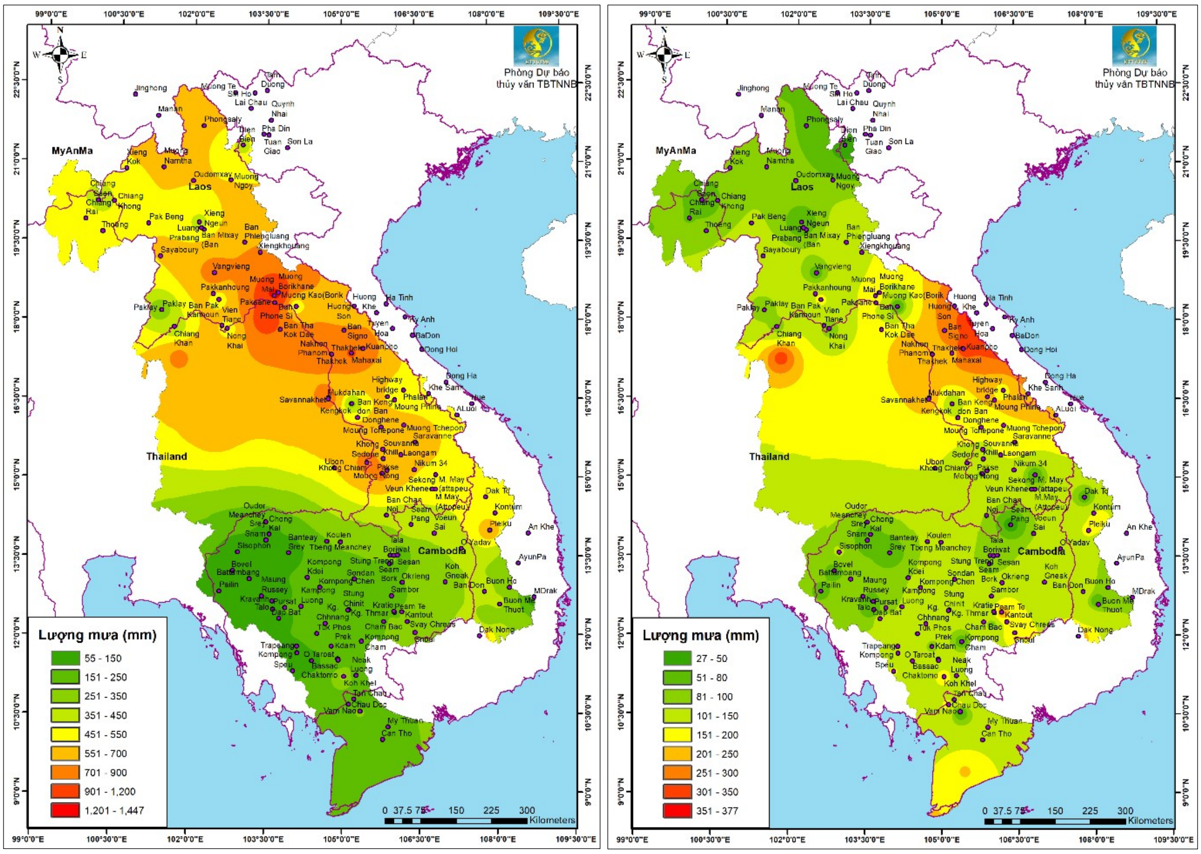


Figure 57: Mean annual precipitation and temperature in Viet Nam

5.4.2 Regional climate in 2017

In 2017, the number of typhoons over the Western North Pacific Ocean was higher than average. About 11 typhoons and 14 depressions occurred in 2017, from which 5 storms/typhoons and 3 tropical depressions made landfall in Viet Nam. The storm season in 2017 was unusually long with the first tropical depression formed in January and the last in December.

The rainy season brought two periods of heavy and prolonged rainfall. The first rain appeared in May with average rainfall of 100-150 mm in the upper Mekong. The two major rain periods occurred from 28 June to 30 July and from 14-27 September. The rainfall distribution is shown in Figure 58. Rainfall over the Mekong Delta was in the range of 100 to 200 mm during the first period and reached more than 200 mm in September (see Table 14).



(Source: National Centre for Hydro Meteorological Forecasting, 2018)

Figure 58: Total rainfall for major rain periods (28/6-30/7/2017 and 14-27/9/2017)

Table 14: Monthly rainfall (mm) 2017 at main hydromet stations in Viet Nam located in the LMB

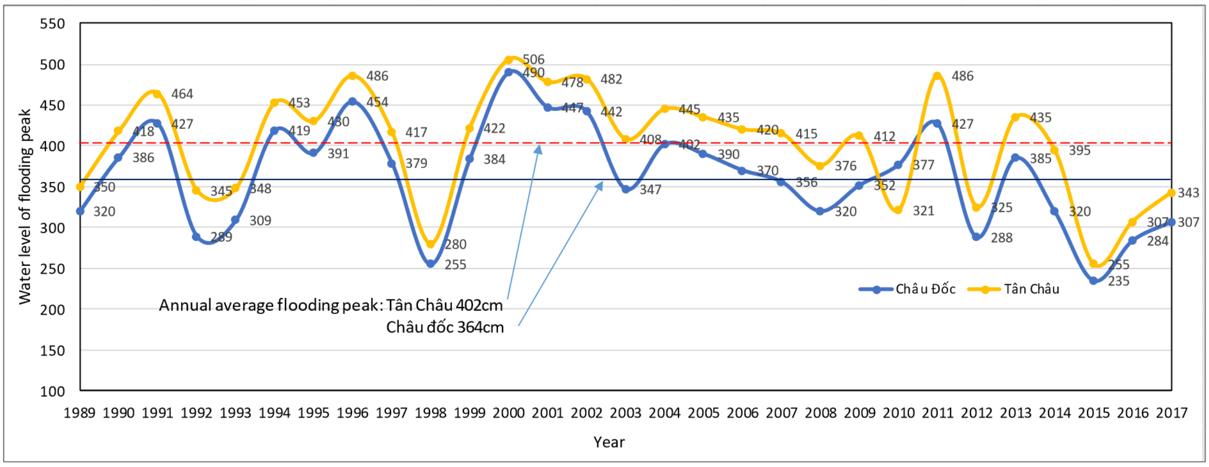
Station	June	July	August	September	October
Kon Tum	171.2	551.9	436.9	228.4	142.2
Pleiku	241.2	617.4	337	232.6	187.7
Buôn Mê Thuột	217.4	282	159.1	149	256.3
Tân Châu	38.3	124.9	138.7	210.6	341.6
Châu Đốc	146	218	137	235	221

(Source: National Centre for Hydro Meteorological Forecasting, 2018)

5.4.3 Hydrological situation in 2017

In the Mekong Delta, floods occur annually with long duration and low intensity. Causes for flooding in the Mekong Delta are the natural flood pulse of the Mekong, natural contribution from Tonle Sap, local rainfall, and backwater effects due to the tide. Nowadays, it seems as if the annual flood pattern has changed, apparently because of water infrastructure development upstream. The flood occurs late, is usually lower than long-term means, and shows a decreasing tendency.

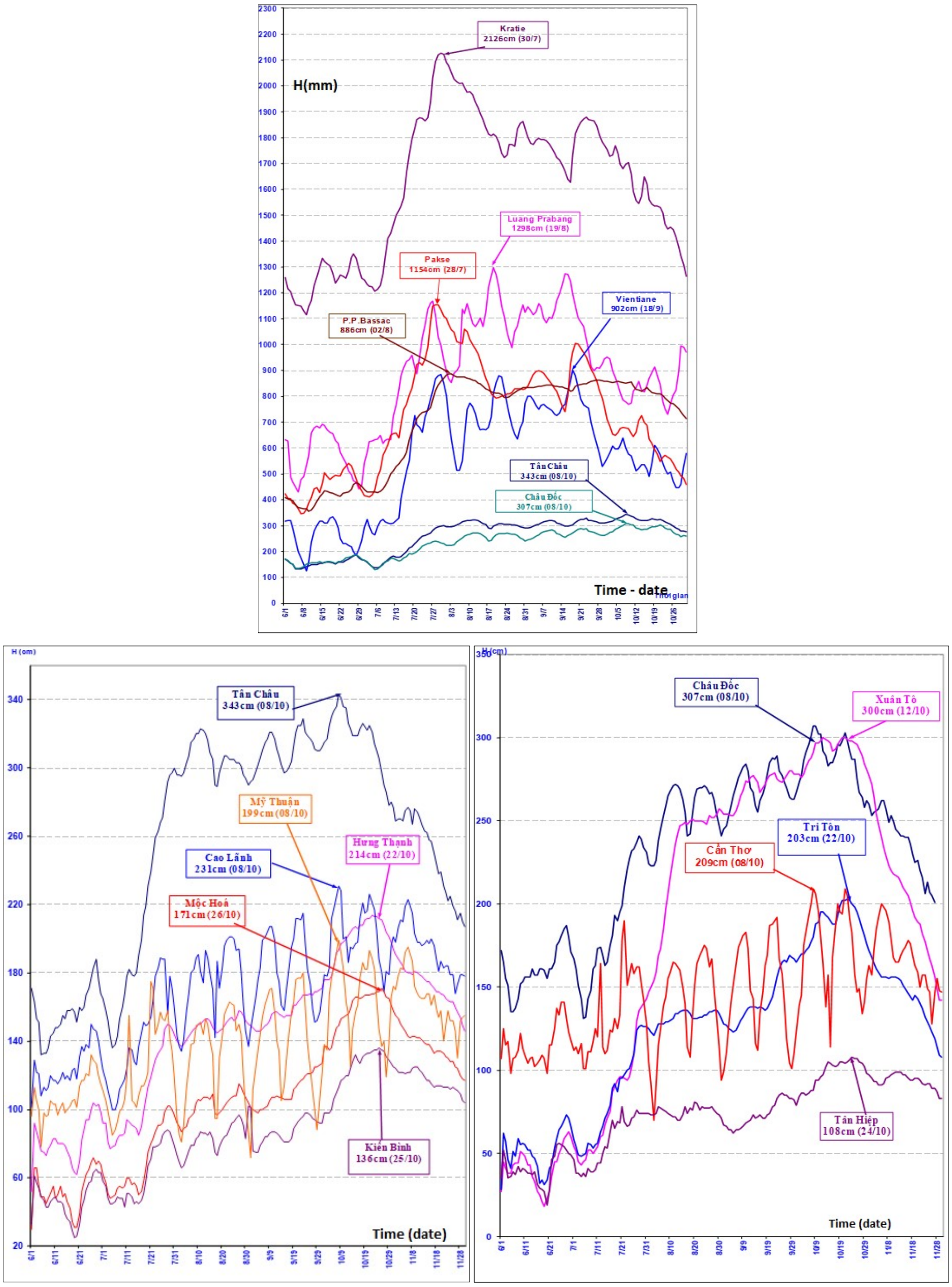
Floods are classified based on water levels at the main stations in the Mekong Delta. High Water is defined when Hmax > 4.5 m MSL and Extreme Flood when Hmax > 5.0 m MSL. Figure 59 shows an extract dating back to 1989.



(Sources: National Centre of Hydrology and Meteorology Forecasting, 2018)

Figure 59: Flood classification and peaks at Tan Chau and Chau Doc Stations, Vietnam

The water level of the Mekong River flow varies in the delta according to the influence of the tides. The water levels on Tien River and Hau River reached their highest peak in October 2017, which was 3.43 m at Tan Chau station and 3.07 m at Chau Doc station both on 8 October.



Sources: National Centre of Hydrology and Meteorology Forecasting, 2018)

Figure 60: Water levels 2017 along the Mekong mainstream in Viet Nam in absolute values

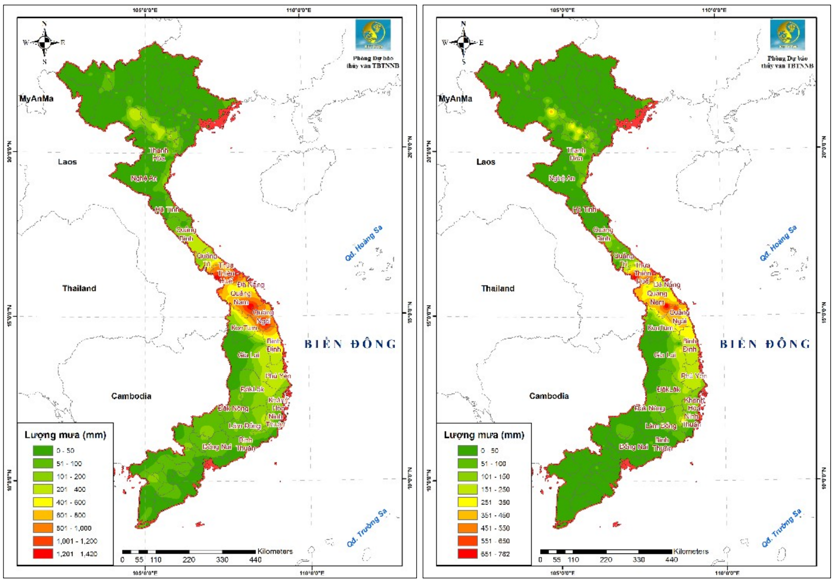
Records of the years since 1926 indicate 20 big flood events observed in the Mekong Delta, of which 9 events occurred as of 1961, namely in 1961, 1966, 1978, 1984, 1991, 1996, 2000, 2001, and 2002. Three of these events exceeded the Extreme Flood Level. The table below indicates the main parameters of extreme events and parameters of recent years at the hydrological stations along the main rivers in Viet Nam.

Table 15: Compilation of hydrological parameters at main stations in Viet Nam

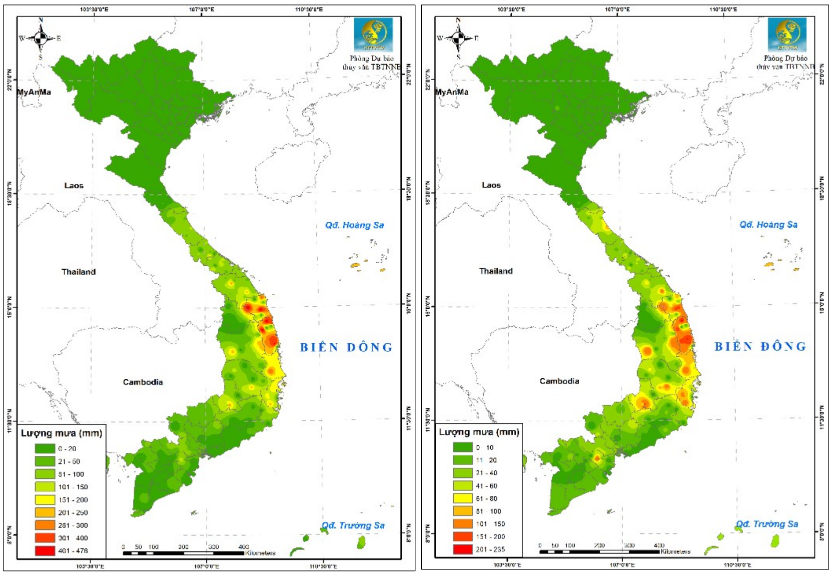
Year	Tan Chau (Mekong River)		Chau Doc (Bassac River)		Moc Hoa (Vaico River)	
	H_{max} (cm)	Q_{max} (m^3/s)/Date	H_{max} (cm)	Q_{max} (m^3/s)/Date	H_{max} (cm)	Q_{max} (m^3/s)/ Date
1961	512	28,800 / 12/10	489	7,840 / 13/10	2.43	*/ 19/10
1966	511	*/ 27/9	484	*/ 28/10	2.50	*/ 3/10
2000	506	25,500 / 23/10	490	7,660 / 23/9	3.27	*/ 25/9
2011	486	*/ 12/10	427	*/ 29/9	280	*/ 28/10
2013	435	*/ 4/10	385	*/ 7/10	*	*
2014	395	*/ 15/8	320	*/ 17/8	*	*
2015	255	*/ 15/10	235	*/ 30/9	*	*
2016	307	*/ 17/10	284	*/ 17/10	147	*/ 26/10
2017	343	*/ 08/10	307	*/ 08/10	171	*/ 26/10

*Source: Central Steering committee for Flood prevention and mitigation losses and the National Centre for Hydro Meteorological Forecasting, 2018; * No data*

Locally confined flash flood events appeared in the Central Highlands. The flood peaks on the rivers from Thanh Hoa Province to Ha Tinh Province appeared mid-October and in Quang Tri Province, Khanh HoP province and Kon Tum Province in November. Thach Hoa Province (Kon river), Ninh Thuan Province and Gia Lai Province had their highest values at the beginning of December. Total rainfall and distribution of the two rainstorm periods are indicated in Figure 61.



Total rainfall and maximum daily rainfall during 4 – 8/11



Total rainfall and maximum daily rainfall during 2 – 5/12

Figure 61: Rain distribution, total rainfall and maximum daily rainfall for major rain periods in 2017, Viet Nam

An overview of natural disasters in 2017 is provided in Figure 62.

Figure 62: Overview of natural disasters in 2017 in Viet Nam[1]

Drought was not an issue in 2017. No incidents of losses due to drought were reported. However, all-time low water levels occurred in rivers in the Central Region of Viet Nam at the beginning of 2017 as a consequence of the drought year 2016.

5.4.4 Impact of flooding/drought 2017

The losses to people and property in 2017, obtained by the Southern Department of Natural Disaster Prevention and Control and the Central Department of Natural Disaster Prevention and Control, are summarized below.

[1] *Central Steering Committee for Natural Disaster prevention and Control, 2018*

Table 16: Summary of flood induced losses and costs in the Mekong Delta and Highlands of Viet Nam for 2017

Category	Item damaged	Unit	MK	Highland	Total
People	Killed	Person	7	12	19
	Injured	Person	4	15	19
	Missing	Person		4	4
	Affected	households	221	7	228
Housing	Houses collapsed, drifted	No	218	721	939
	Houses submerged and damaged	No	1,013	966	1,979
School	School collapsed	Room	14	38	52
	School submerged and damaged	Room			
Agriculture	Rice fields submerged	Ha	9,069	2,501	11,570
	Farms submerged, damaged	Ha			
	Fruit tree area	Ha	227	7,231	7,458
	Food (salt) damaged by water	Ton			
Irrigation	Dyke damage	m	1,160	2,150	3,310
Transportation	Land drifted	m3			
	Bridge, sewer collapsed	Unit			
	Roads damaged submerged	m		9,028	9,028
	Total damage	10^6 USD	5.95	30.35	36.30

Source: The Southern Department for Natural Disaster Prevention and Control and the Central and Department for Natural Disaster Prevention and Control (2018)

6 CONLUSIONS AND RECOMMENDATIONS

After two years with below average precipitation and flow, 2017 showed normal conditions. Still, there are issues that require attention, even though normal conditions were prevailing.

Vulnerability of settlements

There is obviously an increasing tendency of migration from rural to urban settlements. This is reported from Cambodia and is most likely true for Lao PDR, and maybe for Vietnam and Thailand as well. Due to lack of suitable land, migrants will predominantly encroach in sensitive areas such as the immediate vicinity of riverbanks and in the flood plains. As a result, urban settlements become more vulnerable to flooding, particularly if urban planning is unprepared.

Land-use change

A remarkable land-use change driven by population growth is ongoing in the LMB. Alternation of rainforest, wetland, and undisturbed vegetated land due to the legal or illegal timber industry and agricultural activities are ongoing and increase runoff, accelerate flow, and reduce water storage. The climate change-induced higher rainfall intensities will add to these issues. The consequences are higher and accelerated flood peaks.

Water infrastructure development

Another aspect affecting flow hydrographs is the development of dams along the tributaries. Each dam is more or less operated separately and cumulative effects of reservoir operation on downstream river sections are not yet known or analysed. Reservoirs should be able to decrease flood peaks in immediate downstream river sections. However, dam releases can lead to higher and faster rising flood peaks if releases or uncontrolled spill from different dams superimpose adversely due to bad timing.

Flash flood system

Expectedly, the evaluation of the flash flood system showed that the lead time is short. The FFG indicated high risks a few hours ahead on the same day flash floods occurred. It will be very difficult to improve this. However, a second aspect is mentioned in the evaluation report; that is, flash floods occurred even when the FFG system showed risk level 2. One recommendation given in the evaluation report is to issue warnings also for risk level 2 (MRC, 2018). It is recommended to check as to whether current risk level 2 in the FFG for particular situations could be enhanced so that the FFG identifies the high risk and raises to the next higher risk level instead of remaining at risk level 2.

Capacity building

The Member Countries suggested to invest in capacity building regarding emergency preparedness and response, especially at the level of local communities. There are two aspects related to this topic: a) a robust and clear notification chain and b) self-reliant and easy to apply monitoring and emergency preparedness at the local level. Currently, there is a disconnect between flash flood warnings issued by the FFG and taking action at vulnerable places that are difficult to access. It is also difficult to launch response action once damaging flash floods have occurred and access roads are blocked. Therefore, disaster risk committees at local levels should be established. Risk maps should be prepared and communicated indicating risk areas, safe ground, meeting points, etc. Risk maps indicating the exposure of buildings to expected flow paths of flash floods help cope with natural hazards. The latter holds true not only for flash floods but also for riverine flooding.

Data management

Many activities are related to National Early Warning Systems and monitoring. There is a need to coordinate these activities since many upstream-downstream connections among the countries exist. It could be very meaningful if data sharing is included at the very beginning when data management systems are conceived and planned. A direct link is given to the previous topic ‘Capacity building’.

Water demand inventory and water deficit report mechanisms

Unlike flood damage, report mechanisms related to drought induced damages have not been established. This is understandable because effects of droughts are difficult to assess. However, what can and should be undertaken is an inventory of water demand. This helps identify water shortages when water availability is monitored. Effects due to drought conditions can be evaluated based on the deficit between water demand and water availability.

From the viewpoint of MRC, it is necessary to know more about water demand and its spatial distribution. Considering drought monitoring and forecasting as the new task of the RFDMC, it is only a matter of time before information about water deficit is requested in the future. Any water demand inventory requires support from the Member Countries and as such, it is an effort which calls for a coordinated approach. A good example is the strategic water resources analysis carried out by the Nile Basin Initiative. Water demand including projections up to 2050 were collected and documented in a joint effort. Part of the water demand inventory is published here: http://atlas.nilebasin.org/.

Onset and end of the flood season

A definition of the onset and end of the flood season was developed in the second AMFR 2006. Long-term mean annual discharge is used as the trigger separating the year into four seasons: (1) dry, (2) transition dry to flood, (3) flood season and (4) transition back from flood to dry season. This definition is reasonable for natural flow conditions but is difficult when discharge is disturbed by reservoir operation. The start and end of each season is defined by specific flow thresholds rather than by particular calendar days and the date of the onset of seasons may vary from year to year. The recognition transition seasons between the dry and flood seasons is also particularly important because the changes in flow during these times have great biological significance.

Review of stage-discharge curves

Stage-discharge curves of the main reporting stations along the Mekong mainstream require regular checks. The river channel is not static, and changes occur due to sedimentation, erosion, etc. In chapter 2.6, a minimum flow was analysed, and it seems a trend is visible, among others, due to releases from the Chinese dams. However, the effect is not homogenous among the observation sites and goes back to years where no upstream dams affected flow.

Therefore, it is recommended to review and check the stage-discharge curves. The importance is very high since water levels are monitored from which flow is calculated based on the stage-discharge curves. Wrong curves directly affect flow and may lead to wrong assumptions on water availability.

Transboundary water allocation framework

Among others, there are two mounting issues with respect to water allocation in the Mekong River Basin:

- Reverse flow at Tonle Sap
- Salinity in the Mekong Delta

High water levels in the Mekong mainstream are required to trigger reverse flow into the Tonle Sap. For centuries, the natural flow pulse of the Mekong created this natural phenomenon. Nowadays, the difference between dry and rainy seasons is gradually being reduced to a more homogenous hydrograph due to dam development. The more dams are built along mainstream Mekong and in the tributaries, the more homogeneous the hydrograph. It should be clear that the reverse flow phenomenon of the Tonle Sap is the root cause for manifold ecological and associated economic effects that are essential for Cambodia.

The second mounting problem is salinization in the Mekong Delta. Saltwater intrusion will acerbate with a rising sea level and reduced flow from the Mekong. Withdrawals upstream affect the salinity problem and become a sensitive transboundary issue.

The scope of both topics is at river basin scale addressing the four Member Countries of the LMB and China. A concept is needed in which the five countries agree on a legally binding water management framework to ensure the reverse flow into Tonle Sap and to consider salinization problems in the Mekong Delta. Such a framework will take time and must be initiated at an early stage before investment in large dam and water abstraction projects are undertaken without coordination. The UN Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention) aims to ensure the sustainable use of transboundary water resources by facilitating cooperation. This convention is an instrument from which a detailed Mekong River framework could be adopted.

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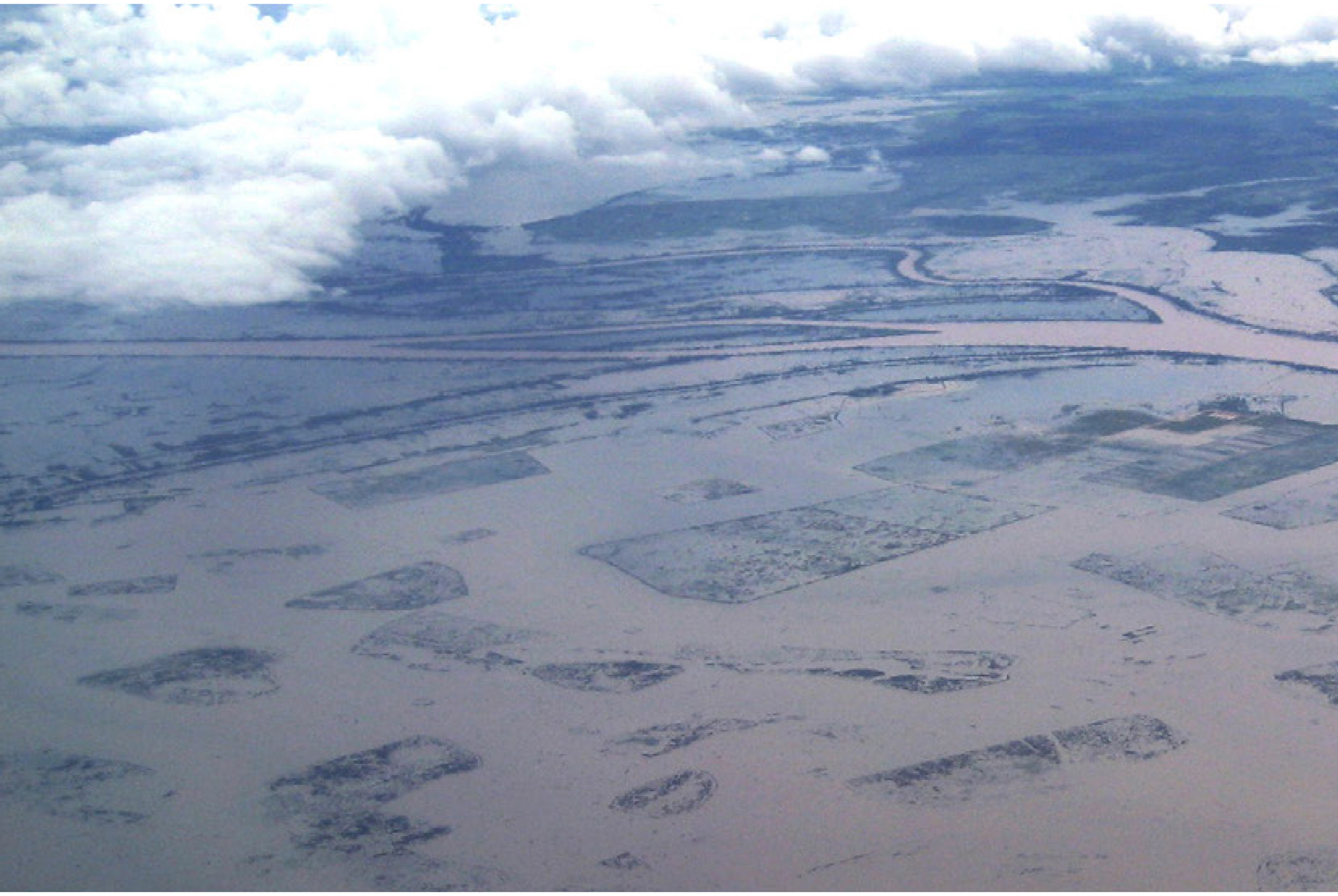

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