Development of Hydrological Model for the Cyclone Komen Event in the Data Scarce Mountainous Watershed: A Case Study in the Mone River Basin, Myanmar

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Abstract: *Cyclone Komen caused the major flooding in the Mone River basin which has two cascade reservoirs at the end of July 2015. Both reservoirs were almost overtopped and the inflow during this cyclone event is found as outlier throughout the life of these reservoirs. Therefore, the basin is needed to develop a hydrological model for the further analysis. This study firstly simulates the inflow from the rainfall to estimate the model parameters for the basin. The satellite rainfall, Tropical Rainfall Measuring Mission (TRMM), is used in combination of available two stations data as an input to the SOBEK, 1D/2D hydrodynamics, rainfall runoff and real time control model to capture a good spatial distribution of the rainfall. Since TRMM overestimates the drizzle days and underestimates the heavy rain, the calibration-validation is carried out on monthly basic from 2009 to 2014 and 2015 to 2017 period respectively. The hydrological model is evaluated as nice performance with the correlation between simulated and observed runoff of 0.8. However, the daily inflow simulation results still fail to represent the outlier of the Cyclone Komen event. The hydrological modelling depends also on the good temporal distribution of rainfall in which using the daily rainfall can fail to get the specific peak. Therefore, the rainfall input is disaggregated to hourly rainfall by HYDROGNOMON 4, a hydrological time series analysis software, to simulate the inflow with better temporal distribution of the rainfall. This study secondly demonstrates the variability and uncertainty in the runoff simulation according to the quality of the model input.*

Key Words: *Cyclone Komen, Hydrological modelling, TRMM, SOBEK, Hourly disaggregation.*

1. INTRODUCTION:

Cyclone which usually fetches heavy rain is one of the catastrophic disasters and leads to the negative socio-economic impacts and loss of human life. During the cyclone, the extreme precipitation not only causes the pluvial flooding but also changes the riverine flow and threatens the safety of the manmade structures such as reservoirs, weirs, bridges, sluice gates in the basin.

In dealing with the flooding problem, many studies recommend to incorporate with the decision support tools in the process for better investigation. Also planning options and rehabilitation actions need to be taken at a river basin scale (Demir and Krajewski, 2013; Filatova, 2014; Sharma et al., 2014; Sprague and Carlson, 1982; Vieira et al., 2012). Generally, flood forecasting and flood management requires statistical analysis of the relevant collected data, and the implementation of hydrological and hydrodynamic models. The hydrological modelling is an essential step in flood management before getting to the desired analysis, for example, investigation of the safety of the dam, flood forecasting, production of flood hazard maps for the downstream area, and so on. However, these models also depict the four main uncertainties; uncertainty in input, uncertainty in output used for calibration, uncertainty in model parameters, and uncertainty and error in model structure (Engeland et al., 2016).

The hydrological modelling in a watershed with high elevation difference is a challenging task due to the complexity of the topography and the hydrological process. In addition, the mountainous regions typically lack of meteorological and hydrological stations. In this case, the satellite rainfall products are crucial in offering an alternative to ground-based rainfall measurement and also have the advantage of good spatial coverage. Nowadays, several data sets are available since the 1980s, such as the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) (Sorooshian et al., 2000), the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) (Huffman et al., 2007), the Climate Prediction Center (CPC) MORPHing technique (CMORPH) (Joyce et al., 2004), and the Global Satellite Mapping of Precipitation (GSMaP) (Ushio et al.,2009), etc. Many studies evaluate these products extensively and generally found that TRMM and CMORPH achieve the considerable accuracy in monthly scale (Thiemig et al., 2012) and the 3B42 V7 product tends to produce a relatively higher accuracy among the various TRMM products in daily scale (Zulkafli et al., 2014).

Myanmar usually receives the tropical cyclone from the Bay of Bengal (BOB) from May to late October. On the 26 July 2015, the Cyclone Komen brought torrential precipitation (JTWC, 2015) and continued with the rain started from 16 July resulting the severe flooding in various parts of the country. The government declared the state of emergency in the four worst-hit regions in the west - Magway Region, Sagaing Region, Chin State and Rakhine State on 30 July. During the Cyclone Komen event, two cascade multipurpose reservoirs in the Magway Division received unexpected extreme inflow and almost overtopped. The two high earthen dams are located on the downstream of the Mone River and the failure of these dams will absolutely result in huge property damage and loss of life. Therefore, the Mone River basin is selected as a case study to develop a rainfall runoff model which can be used as a tool for the future study.

This study aims (1) to examine the applicability of TRMM for a basin with high elevation difference, (2) to develop a hydrological model for the Mone River basin, and (3) to redevelop the extreme Cyclone Komen inflow peak for the further analysis.

The main challenge for this study is that the basin is a sparsely gauged mountainous watershed. There are no long-term meteorology and hydrology stations in the basin. In this study, TRMM 3B42 V7 rainfall product together with the available dam rainfall is used as a model input for better spatial distribution and the measured inflow to the reservoir is used in the model calibration-validation. Therefore, the high uncertainty in modelling work is expected and the calibration-validation is carried out in the monthly basic. In reconstructing the extreme streamflow peak for the Cyclone Komen, the rainfall input is disaggregated into hourly to have a better temporal resolution and explore the large range of the variability in the output of the hydrological model depending on the quality of the model input.

2. STUDY AREA:

The Mone River basin is located in the Western part of Myanmar covering an area about 5990 km^2. The Mone River as its main river has length of 296 km, originates from Mount Victoria (3,067 m.a.s.l), which is the highest mountain in the Chin Hills, passes through the Magway Region and flows into the Ayeyarwady River (Figure 2.1). The downstream part of Mone River has meandering profile before it discharges into the Ayeyarwady River.

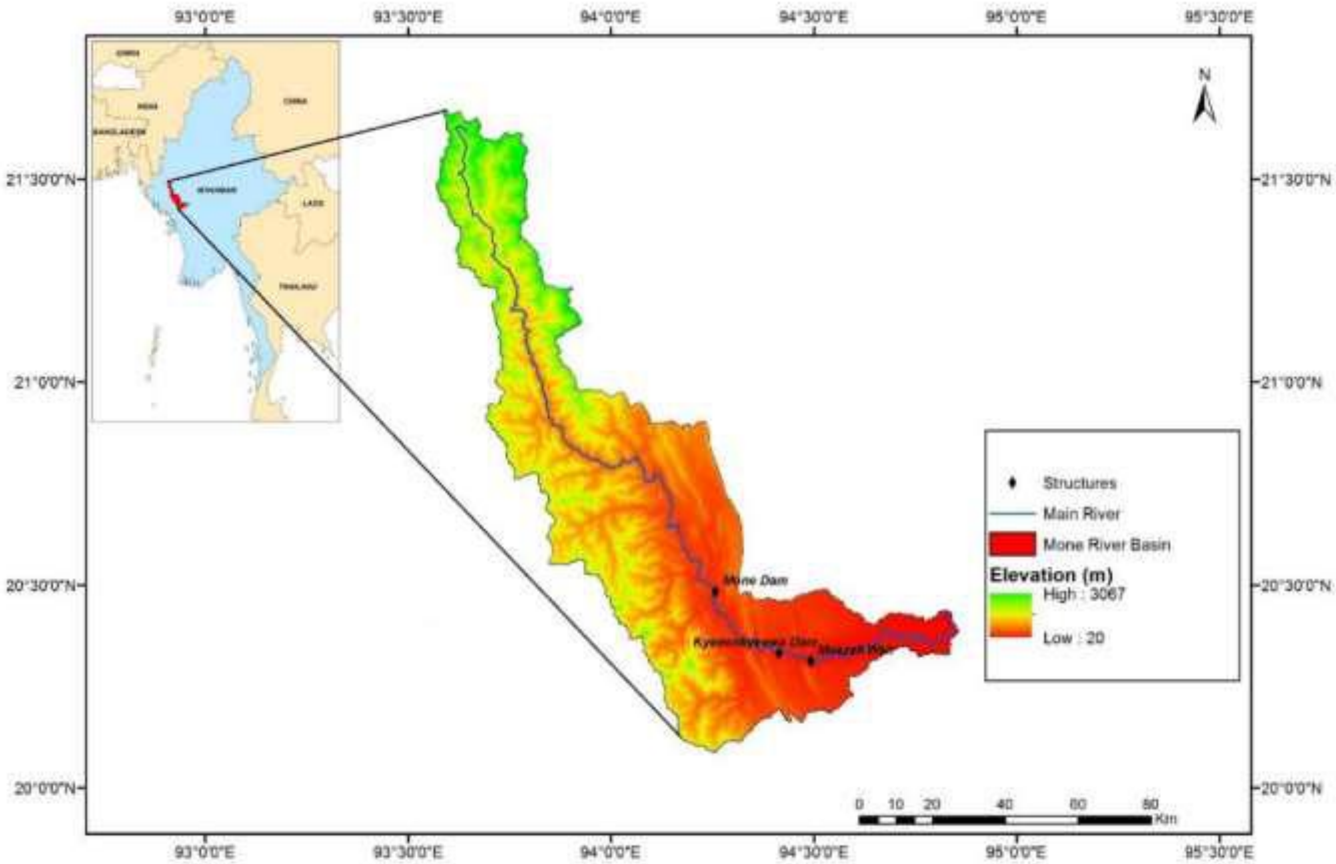

Fig.2.1 Location Map of the Study Area

The Mone River basin is moderately elongated in shape and has high elevation difference varying from 3,067 to 20 m.a.s.l. The upstream and western part of the basin is mostly covered by forest, while the lower part is the agricultural area and settlement.

The Mone River basin has humid subtropical and tropical savanna climate, with distinct humid and dry season. The monsoon season starts from June and lasts until September. Almost 70% of annual precipitation receive from these four months. The average annual rainfall is approximately 1900 mm in the upper portion and decreases to 1600 mm in the middle portion and 1000 mm in the lower portion of the basin.

There are two cascade reservoirs: Mone and Kyee On Kyee Wa and one weir: Mazeli on the main river of the basin. Both reservoirs are multipurpose reservoirs for irrigation water supply and hydropower generation. The Mone and Kyee On Kyee Wa reservoirs can supply 43700 ha and 38850 ha of irrigation water respectively and generate 150 MW electricity in total.

3. MATERIALS:

3.1 Data Used

The data used in this study for the rainfall runoff model calibration and validation are described below with three categories: topography, meteorology, and hydrology.

Topography: The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2) is used for the watershed delineation and extraction of river cross sections to use in the model. The ASTER GDEM with 30 m resolution can be freely downloaded in GeoTIFF format at https://earthexplorer.usgs.gov.

Meteorology: The measured time series of rainfall at the Mone dam site by Ministry of Agriculture, Livestock and Irrigation (MOALI) is available from 2009 to 2017 in daily scale and this in-situ data is used together with the satellite rainfall product, TRMM, to have the better spatial variation.

Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) is a joint mission between NASA and the Japanese Aerospace Exploration Agency (JAXA). The gridded rainfall is provided in 0.25° x 0.25° spatial resolution. It offers the precipitation for the tropics covering the latitude belt from 50°N to 50°S. The satellite was launched in 1997 and the product has the temporal coverage from 1 January 1998 to the present.

TRMM rainfall product can be available in real time and post-real time (research quality) format. Among them, the latest version research quality product, 3B42 Version 7, is used for this study. Version 7 and its predecessor, Version 6 are compared with the rain gauges in and around the Northern Peruvian Andes by Zulkafli et al. (2014). It was found that the Version 7 data have a significantly lower bias and an improved representation of the rainfall distribution. The daily 3B42V7 gridded rainfall is downloaded through http://mirador.gsfc.nasa.gov in the netCDF-4 format.

Hydrology: As mentioned above, the study area does not have the streamflow measurement. Therefore, the inflow estimation by the MOALI at the Mone dam site is used for the model calibration from 2009 to 2014 and validation from 2015 to 2017.

3.2 SOBEK – Sacramento Model

SOBEK is a modelling suite developed by DELTARES for the integral water solutions. With its 1D and 2D domains, it can calculate the flow in simple or complex channel networks with structures and simulate the flooding as a total water management solution. SOBEK consists of a set of integrated modules and allows to simulate rainfall – runoff models in watersheds and flood routing along the river channels and also in the reservoirs separately or in combination (DELTARES, 2016). In this study, SOBEK model version 2.15.001 is used.

One of the available hydrological modules of SOBEK is based on the Sacramento model. This is a conceptual model that uses average precipitation and potential evapotranspiration data to estimate the flow rate in the basin. (Gibertoni et al., 2014). The Sacramento model is integrated in SOBEK in a semi-distributed approach. It implies that a catchment is divided into a number of segments, which are interconnected by the channel reaches. In each segment, rainfall is transformed into runoff towards the main river system. Within each segment, areal homogeneity of rainfall input and basin characteristics is assumed (DELTARES, 2016).

The conceptualization of the processes in the segment module is presented in the following figure.

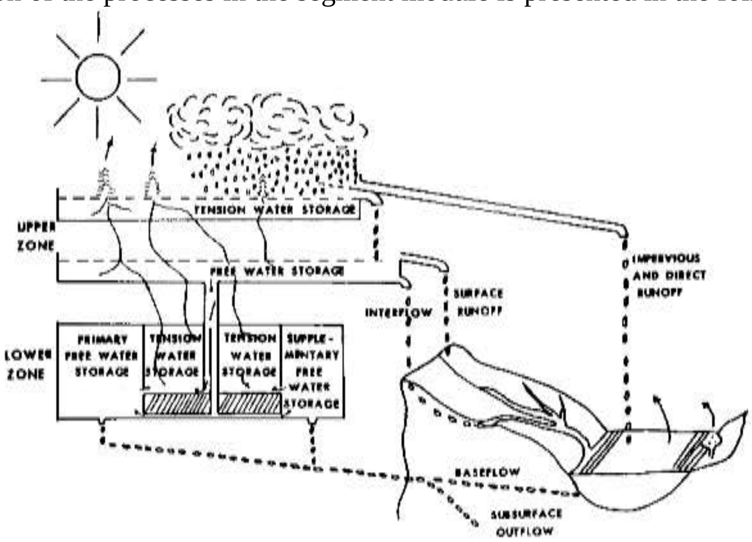

Fig.3.1 Conceptualization of the Rainfall-Runoff Process in a Segment (DELTARES, 2016)

The segment module is divided into the following components.

- Impervious area with transfers to direct runoff
- Pervious area
  - Upper zone
    - Tension storage with transfers to evaporation, free water storage
    - Free water storage with transfers to evaporation, percolation
    - Surface runoff and interflow
  - Lower zone
    - Tension storage with transfers to evaporation, free water storage
    - Free water storage with transfers to baseflow

From the impervious areas, precipitation immediately discharges to the channel. However, impervious areas, which drain to a pervious part before branching the channel, are not considered impervious. Both zones have a tension and a free water storage element. Tension water is considered as the water closely bound to soil particles. Generally, first the tension water requirements are fulfilled before water enters the free water storage (DELTARES, 2016).

4. METHODOLOGY:

4.1 Precipitation Data Preparation

With 0.25-degree (about 27.75 km) resolution, the gridded TRMM rainfall covers the whole Mone River basin with 19 grids. In order to combine with the observed rainfall, the measured Mone dam rainfall is used at the grid, where the structures are located, in preference to the TRMM rainfall. The data covers from 2009 to 2017 on a daily basis. The coverage of the TRMM grids over the study area together with the sub catchments, which are prepared in the Arc-GIS (ESRI) software, is shown in Figure 4.1 and the mean annual rainfall from 1998 to 2015 in each 0.25-degree grid is also shown to exhibit the spatial distribution pattern of the TRMM rainfall estimates.

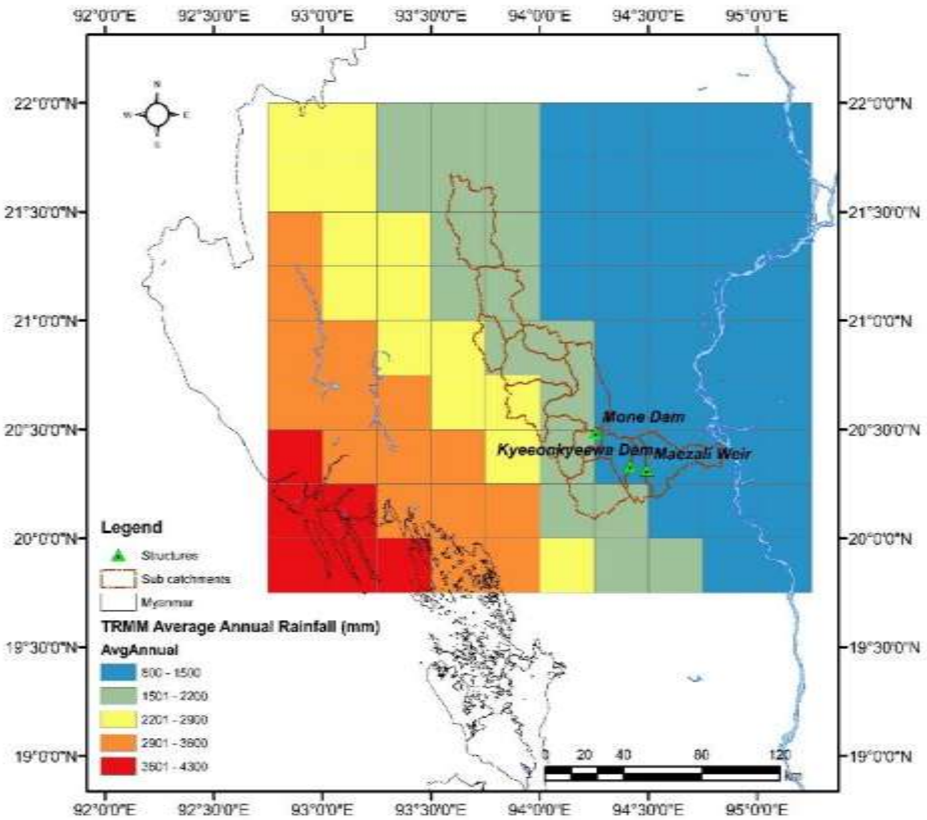

Fig.4.1 Spatial Distribution of TRMM Rainfall with Grids in and around the Study Area with Sub-basins

The gridded TRMM rainfall is transformed to the area rainfall for each sub-basin by the area average approach given by,

$$P = \frac{\sum_{i=1}^{n} P_i A_i}{\sum_{i=1}^{n} A_i}$$

Where P is the daily sub-basin rainfall (mm). P_i is the daily grid rainfall (mm) and A_i is the basin area correspondence to each grid (km^2).

4.2 Hydrological Modelling

The rainfall-runoff transformation is carried out in the SOBEK model with the hydrologic module, Sacramento method. This paper presents the calibration-validation of the inflow at the upper reservoir, Mone. Therefore, the upstream boundary node is assigned at the origin of the Mone River and downstream boundary node at the Mone dam location. Two boundary nodes are linked by the channel flow to perform the channel routing along the river. The cross sections of the river are extracted from the ASTER GDEM and set along the flow channel. One Sacramento rainfall node is assigned in each sub-catchment and linked to the channel flow by rainfall-runoff link with a connection node on the channel. The Sacramento model set up in SOBEK for the Mone River Basin is shown in the following figure.

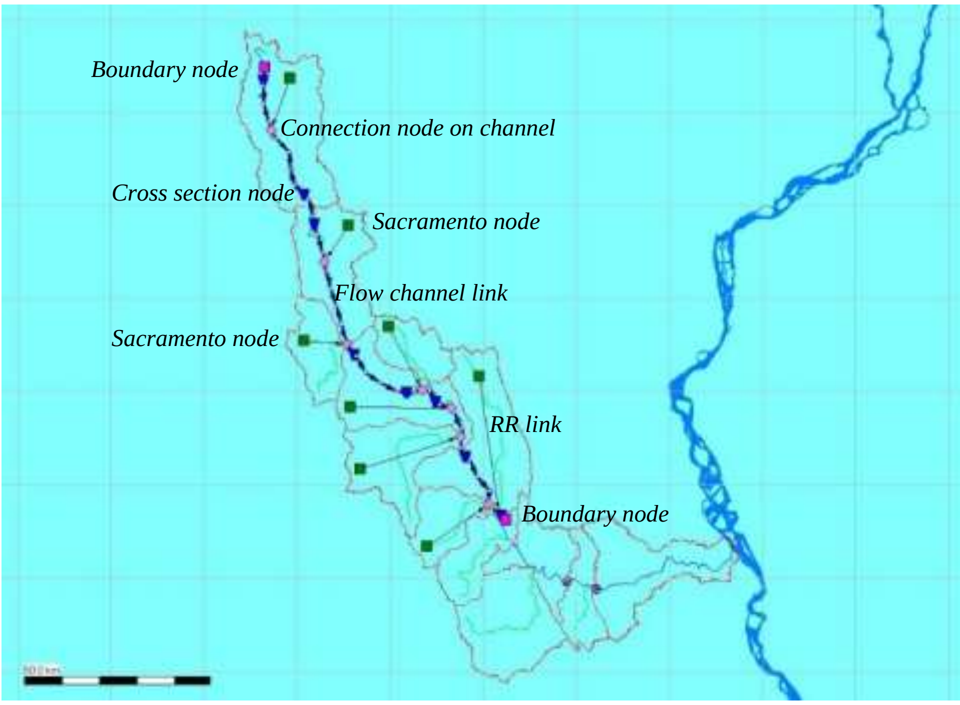

Fig.4.2 Schematization of the Sacramento Rainfall Runoff Model in SOBEK

The model performance is evaluated by the statistical parameters: the Nash Sutcliffe Model Efficiency (NSE), the Correlation Coefficient (CC), and the Coefficient of Determination (R^2). The perfect score for each parameter is 1, which means that the closer to the value 1, the better the model performance is. The calibration period is from 2009 to 2014 and validation period is from 2015 to 2017. According to the prior data quality analysis, TRMM overestimates the drizzle days and underestimates the heavy rain. The observed inflow at the dam site is also high in uncertainty due to the variation in the measured water level in the reservoir and the error in the estimated capacity curve of the reservoir since the inflow is recalculated from the measured water level. Therefore, the parameterization is carried out on the monthly basis since the high uncertainty in both model input and output is foreseen.

4.3 Hourly Rainfall Disaggregation

Running the model with daily rainfall adopts that the precipitation is uniformly distributed over the whole day. This assumption can make the model fails to capture the peak since the detailed information is lost during the aggregation of the daily rainfall. In the analysis of extreme event, the capture of the peak is very important because this can cause the critical situation of the analysis. Therefore, the daily model input rainfall is disaggregated into hourly to explore the variability of the output according to the temporal resolution of the input and to study the ability of the reconstruction of the Cyclone Komen event peak from the hourly rainfall by the model.

The time series processing system Hydrognomon, is an independent open source software application, developed at the National Technical University of Athens (NTUA) by the "Itia" research team. It can be used for the management and analysis of the hydrological data. The available processing techniques for the tool include time step aggregation, disaggregation, and regularization, interpolation, regression analysis and infilling of missing values, consistency test, data filtering, graphical and tabular visualization of time series. The 4th version, used in this study can be freely downloaded at http://hydrognomon.org and the documentation is also available at http://openmeteo.org.

In time series disaggregation, Hydrognomon provides simple tools which can be used in the partition of the values of the time series, for the purpose to generate a time series of smaller time step (Kozanic et al., 2010). The disaggregation can be performed by the uniform distribution or the random term. The random terms can be input as follows:

- Uniform distribution: U_i, values interval (0,1)

- Exponential model: $e^{-U_i} - e^{-1}$, values interval $(0, 1-e^{-1})$
- Logarithmic model: $-\ln (U_i + \varepsilon)$, values interval $(0, -\ln \varepsilon)$, ε is set equal to 10^{-8}
- Square model: U_i^2, values interval (0, 1)
- Higher order model: U_i^b, values interval (0, 1), b is set equal to 12

Among the different disaggregation terms, it is more appropriate to choose the most relevant term for the study area if there is the observed hourly rainfall. However, this paper will be mainly focused on the reconstruction of the Cyclone Komen peak and the study on the variation of the inflow model output according to the different rainfall input patterns.

5. RESULTS AND DISCUSSION:

5.1 Model Calibration and Validation

Model calibration and validation is an essential step to optimize the model parameters of the study area before getting to the desired analysis. The TRMM satellite rainfall product can capture the precipitation spatially and temporally but not so well quantitively for the study area especially in the mountainous regions based on the prior data quality analysis. Moreover, the observed dam inflow used in the model calibration is also estimated from the measured water level in the reservoir. Therefore, the high uncertainty in both model input and output is foreseen and the model parameterization is performed on the monthly basis. The model parameters are calibrated for the period 2009-2014 and validated for the period 2015-2017. The study area covers the upper Mone River basin up to the Mone reservoir. The optimized parameters for the study area are shown in Table 5.1.

Table 5.1. SACRAMENTO PARAMETERS USED IN SOBEK MODEL

Parameter	**Description**	**Estimated Value**	**Acceptable Range**
UZTWM	The upper layer tension water capacity, mm	15	10 – 300
UZFWM	The upper layer free water capacity, mm	100	5 – 150
UZK	Interflow depletion rate from the upper layer free water storage, day^{-1}	0.5	0.1 – 0.75
ZPERC	Ratio of maximum and minimum percolation rates	200	5 – 350
REXP	Shape parameter of the percolation curve	3.3	1.0 – 5.0
LZTWM	The lower layer tension water capacity, mm	120	10 – 500
LZFSM	The lower layer supplemental free water capacity, mm	150	5 – 400
LZFPM	The lower layer primary free water capacity, mm	230	10 – 1000
LZSK	Depletion rate of the lower layer supplemental free water storage, day^{-1}	0.05	0.01 – 0.35
LZPK	Depletion rate of the lower layer primary free water storage, day^{-1}	0.004	0.001 – 0.05
PFREE	Percolation fraction that goes directly to the lower layer free water storage	0.2	0 – 0.8
PCTIM	Permanent impervious area fraction	0.25	Not given
ADIMP	Maximum fraction of an additional area due to saturation	0.45	Not given
RSERV	Fraction of lower layer free water not transferable to lower layer tension water	0.3	Not given

With these estimated parameters, the hydrological model is evaluated as acceptable performance. In the calibration phase, the statistical evaluation parameters are nice seeing that Nash Sutcliffe Model Efficiency (NSE) is 0.5, the Correlation Coefficient (CC) is 0.8, and the Coefficient of Determination (R^2) is 0.7. Validation of the model is done for the time period from 2015 to 2017. Figure 5.1 presents the graph for the observed and simulated monthly inflow together with the rainfall for the calibration and the validation period. As can be seen in Table 5.2, the evaluation values in the validation phase are superior than that in the calibration phase according to the NSE value. Figure 5.2 presents the scatter plot of simulated daily inflow and the observed one. In daily simulation, the observed and the simulated inflow are in general agreement, but still there are several mismatches in high peak values and some low flows with the correlation of 0.6 to 0.7 for the calibration and validation periods respectively.

Table 5.2. SUMMARY OF THE MODEL EVALUATION PARAMETERS

		NSE	CC	R^2
Monthly	Calibration	0.52	0.83	0.69
	Validation	0.61	0.82	0.68
Daily	Calibration	-	0.57	0.32
	Validation	-	0.67	0.45

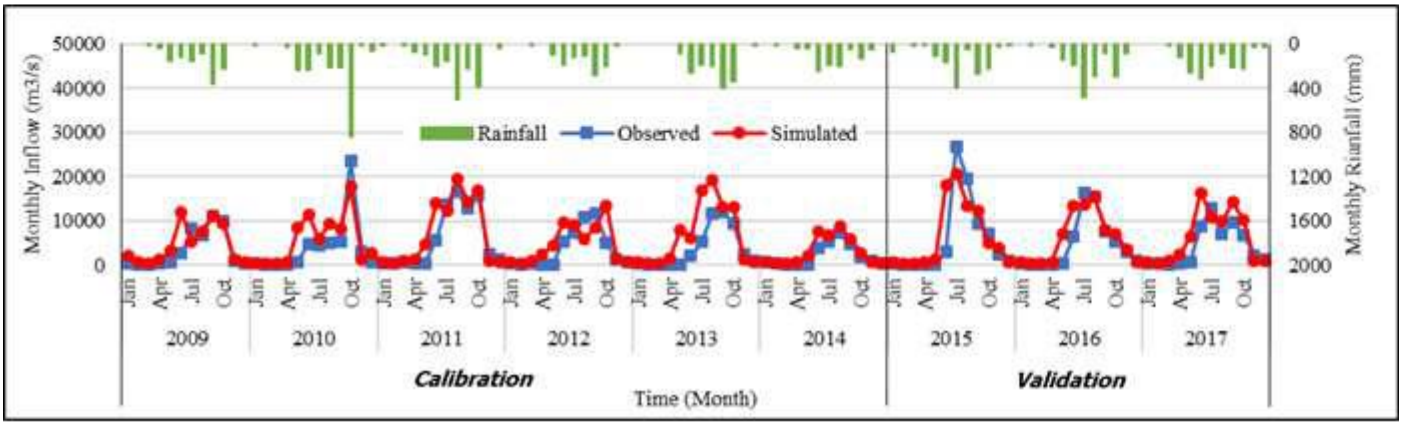

Fig.5.1 Monthly Observed and Simulated Inflow with Mone Dam Rainfall in Calibration and Validation Period

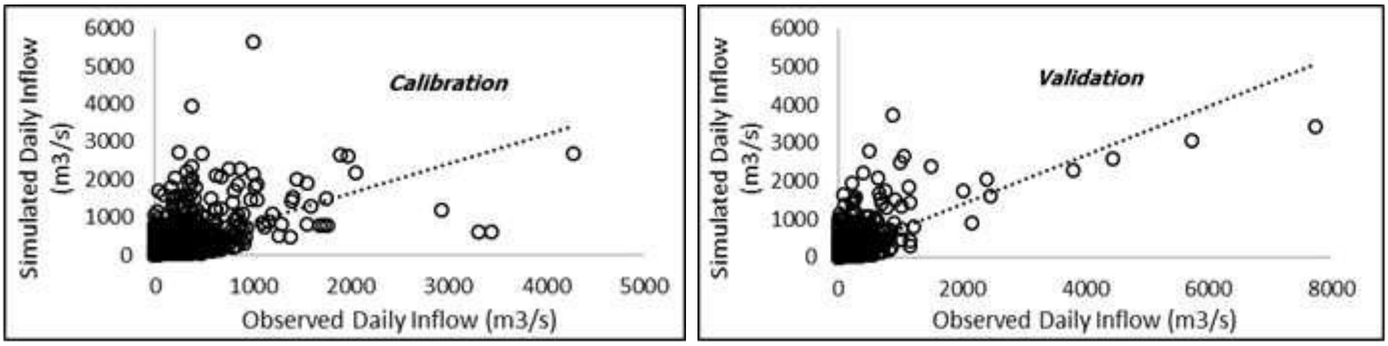

Fig.5.2 Scatter Plot of Daily Observed and Simulated Inflow in Calibration (Left) and Validation (Right)

5.2 *Variation in Simulated Inflow Depending on the Temporal Disaggregation*

After the model validation, the simulation is performed by hourly rainfall input to explore the variation in the simulated runoff according to the different pattern of disaggregation and to study the better performance in capturing the extreme peaks by improved temporal resolution. In this study, the daily TRMM rainfall is disaggregated to hourly by Hydrognomon with four models; (1) Uniform, (2) Exponential, (3) Logarithmic, and (4) Square and the comparison of disaggregation pattern of these four models is shown in Figure 5.3. The simulated runoff graphs by different disaggregation models for the selected events are also shown in Figure 5.4 together with the daily simulated runoff.

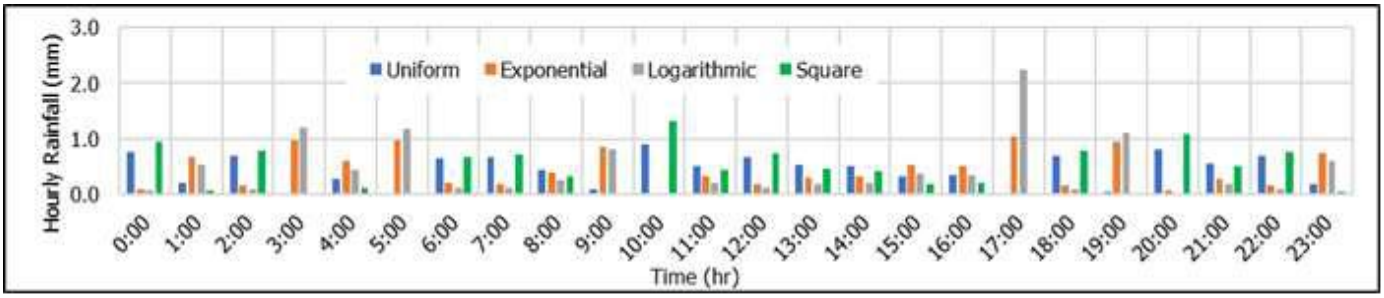

Fig.5.3 Comparison of Hourly Disaggregation Models

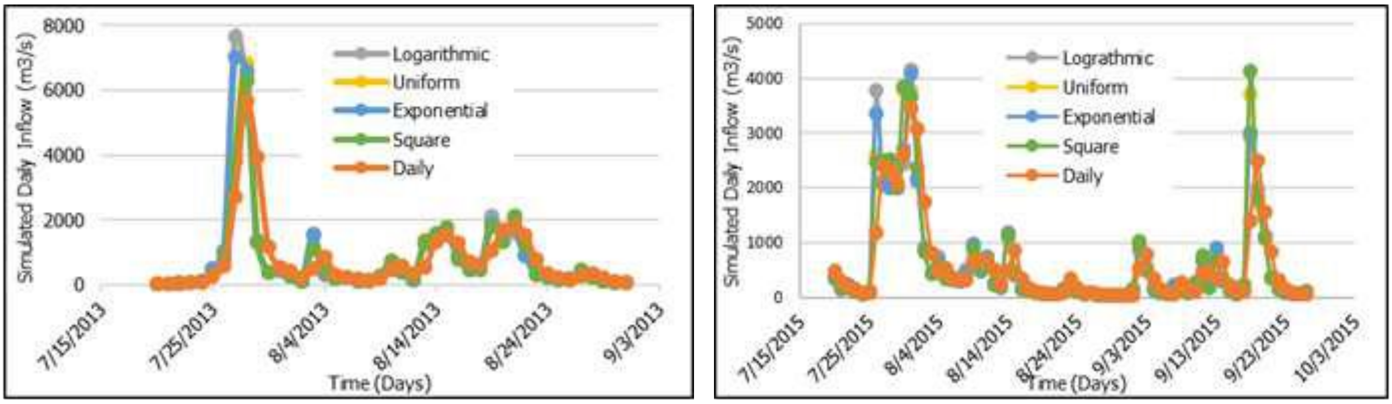

Fig.5.4 Spaghetti Plot of Simulated Inflow by Disaggregation Models for 2013 (Left) and 2015 (Right) Events

From the above graphs, it can be seen that the variation in the temporal rainfall distribution can cause the high uncertainty not only in the peak but also in the timing of the simulated runoff.

5.3 Study on the Redevelopment of the Cyclone Komen Peak for the Further Analysis

For the analysis focusing on the extreme event, the capturing of the peak is one of the most important entities since this peak can cause the critical statement of the problem. In the Mone River basin, the Cyclone Komen peak caused the critical condition on the safety of the dam. Therefore, the capturing of this critical peak by the model is crucial to proceed the further analysis for the dam safety aspect. Based on the different model simulations, the actual Cyclone Komen peak can be redeveloped in the 2013 event, but not in the 2015 event. The reason lies on the underestimation of TRMM rainfall during the extreme cyclone event. If the observed rainfall with better spatial resolution is available, the model performance will be significantly improved. However, for the further analysis of the Mone River Basin by considering the Cyclone event like Komen, the validated hydrological model by this study can offer the redevelopment of the extreme peak by the simulation of the hourly disaggregated rainfall by Logarithmic method.

6. CONCLUSION:

In this study, the hydrological model for the Mone River basin is developed by SOBEK with the application of TRMM rainfall estimate. The model performs acceptable though the simulation of the critical peaks still challenging due to the quality of the rainfall product and the uncertainty in the estimation of the observed inflow used for the calibration process. Generally, TRMM can capture rainfall spatially and temporally but not so well quantitatively since it overestimates the drizzle days and underestimates the heavy rain. However, for the data scarce region like Mone River basin, it is a good alternative to develop the model and study the future scenarios in case of extreme event like Cyclone Komen.

This study also explores the different hourly disaggregation patterns of rainfall and discovers how these temporal resolutions and timings can affect the output of the model runoff. In case of redevelopment of the Cyclone Komen peak, which is the most critical condition for the reservoirs, the hourly disaggregation by Log model can simulate the critical peak again in 2013 rainfall event although the model fails to capture the peak in 2015 again due to the underestimation of TRMM rainfall during the cyclone. Therefore, by the application of this calibrated model with the 2013 rainfall event, the further analysis such as dam safety analysis can be carried out as future aspects of the study.

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