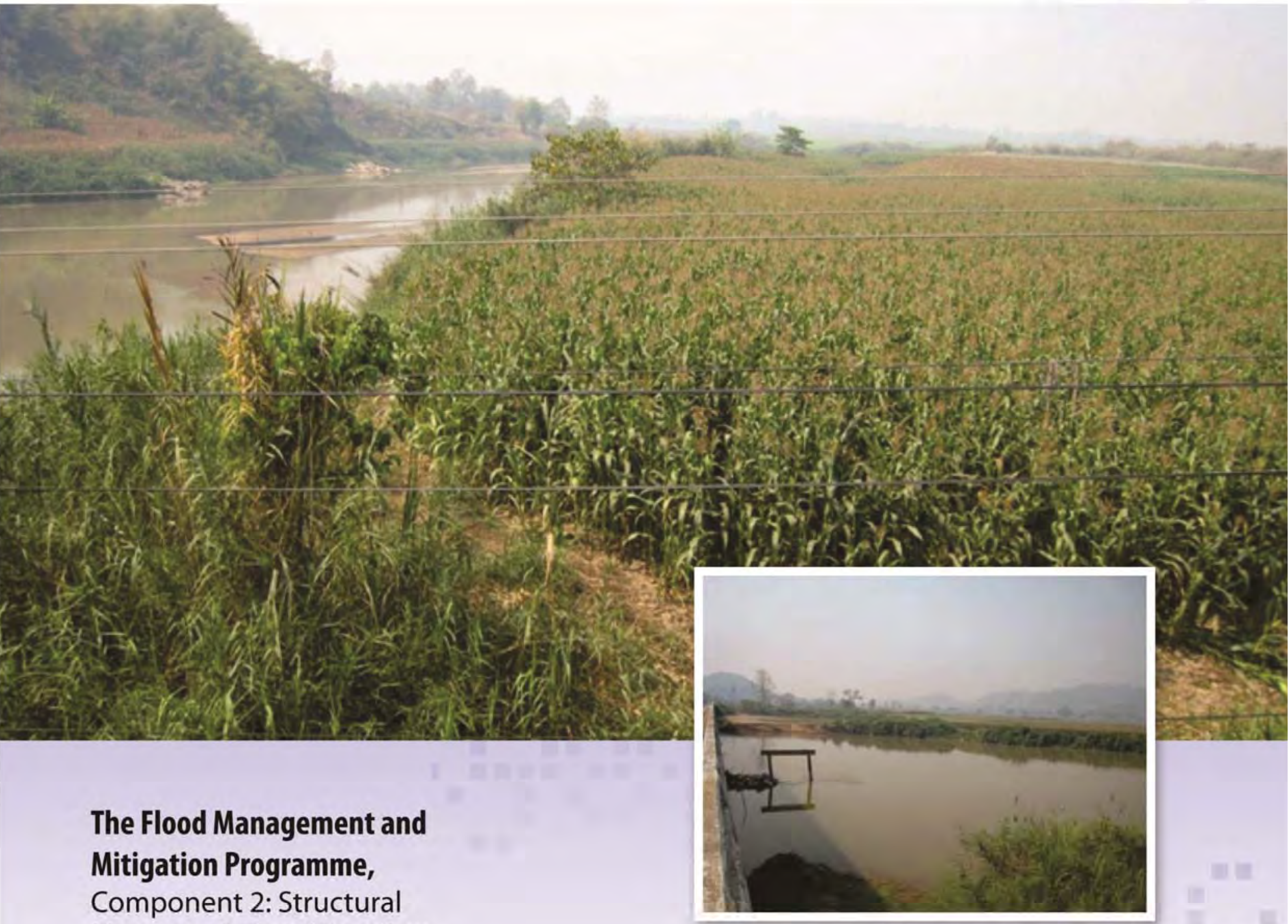
MEKONG RIVER COMMISSION
MRC
FOR SUSTAINABLE DEVELOPMENT

Flood Risk Assessment in the Nam Mae Kok Basin, Thailand



The Flood Management and Mitigation Programme,
Component 2: Structural Measures & Flood Proofing in the Lower Mekong Basin

May 2010
Final Report, Volume 6A

Deltares
Enabling Delta Life Delft Hydraulics

ROYAL HASKONING

UNESCO

Mekong River Commission

Flood Management and Mitigation Programme

Structural Measures and Flood Proofing in the Lower Mekong Basin

Flood Risk Assessment in the Nam Mae Kok Basin, Thailand

Volume 6A

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Editors have applied, to the extent possible, the MRC standard for names of rivers, villages, districts and provinces. However some names in maps, figures and tables could not be timely adjusted as a result of the picture-format used by the authors.

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SUMMARY

This report presents the findings of the FMMP-C2 Demonstration Project that aims to assist Thailand in ***Flood Risk Assessment*** in the Nam Mae Kok Basin in Chiang Rai Province in Thailand.

Based on the analyses presented in the report the following conclusions can be drawn.

Flood prone area in the Nam Mae Kok Basin comprise:
Valley of Nam Mae Fang River
Chiang Rai Province, and
Mouth of Nam Mae Kok River.

Floods in the upper reaches of the tributaries are flashy. Flashiness decreases further downstream in the Chiang Rai region. In the lower 20-25 km of the Nam Mae Kok near the mouth the flood levels are affected by backwater from the Mekong.

Extreme value distributions of peak flows and the possible range of flood volumes can be used for assessment of the hydrological hazard in the Chiang Rai region regarding peak levels and flood duration. A bivariate distribution should be used for the river mouth area.

Data availability and validation
Water level and discharge series of sufficient length are available to assess the hydrological hazard in the Chiang Rai region and near the Nam Mae Kok mouth.

Validation of hydrological data does not appear to be common practice according to sources at the data collecting agencies.

The applied stage-discharge relations for the stations on Nam Mae Kok and tributaries varied strongly from year to year. The number of discharge measurement taken each year suggests that the changes are due to morphological developments in the station controls. Some re-settings of gauges to different gauge zeros seem to have occurred, but have not been recorded.

Whereas the rainfall records are mutually consistent, the discharge series are not. Distinct changes in the records are apparent in the series of Ban Pang Na Kham in the period 1988-1994, whereas the series of Ban Mae Phaeng is inconsistent with the area adjusted sum of the Kok and Lao flows for almost its entire record.

As a consequence of the Ban Mae Phaeng inconsistency, the SWAT based lateral inflows are overestimated by a factor 2.3.

Hydrological characteristics
Annual rainfall in the Kok basin is largest towards the river mouth (1,700 mm) with lower values of 1,300 to 1,400 mm in the upper reaches of the Nam Mae Kok and the Nam Mae Fang. Rainfall is highest in the months July-September.

Evaporation peaks in April-May. Annual totals vary from 1,300 to 1,500 mm. It exceeds rainfall in the period November-April.

The annual average flow volume of the Nam Mae Kok at mouth is about 5.24 BCM. Runoff of Nam Mae Kok at Chiang Rai per unit area is twice the runoff of the Nam Mae Lao. At Chiang Rai

the runoff is highest in the months August and September, whereas in Nam Mae Lao September is the month with the largest flow volume.

The regime of the Nam Mae Kok is a few weeks in spate relative to the Mekong regime.

Hydrological hazard
The hydrological hazard expressed as extreme discharge for selected return periods with a full range of flood volumes have been determined for the Nam Mae Kok at Ban Pong Na Kham, the Nam Mae Lao at Ban Pong Pu Fuang and the Nam Mae Kok downstream of the Loa confluence. Generally, the GEV fits best to the data, but due to the limited data length, the EV1 is not rejected as an alternative.

The annual discharge peaks on the Nam Mae Kok at Ban Pong Na Kham and the Nam Mae Lao at Ban Pong Pu Fuang do generally not occur at the same time. This should be included in the selected boundary conditions for flood hazard assessment with the hydraulic model.

EV1 and GEV distributions fit well to the marginal distributions of observed annual maximum flood peaks and annual flood volumes in the Mekong at Chiang Saen.

The bivariate distribution of annual flood peaks and flood volumes in the Mekong at Chiang Saen can be described by regression equations and GEV-distributions for the regression residuals.

The observed distribution of annual flood volumes in the Nam Mae Kok is well described by an EV-1-distribution.

The bivariate distribution of annual flood peaks and flood volumes in the Nam Mae Kok at mouth can be described by regression equations and GEV-distributions for the regression residuals.

Neither the peak discharges nor the annual flood volumes in the Mekong versus the Nam Mae Kok show significant correlation.

The annual maximum discharges on the Mekong occur on average about two weeks earlier than the annual peaks on the Nam Mae Kok.

Flood hazard
The flooding around Chiang Rai City is complex and its extent is preferably modelled with a 1D/2D hydraulic model.

The existing hydraulic model of the Nam Mae Kok River needs to be adjusted in the cross-sections particularly for the Nam Mae Lao River and recalibrated using appropriate lateral inflows for reliable flood hazard assessment.

A full range of hydrographs (flood peaks and related range of flood volumes) have been developed for flood hazard computations around Chiang Rai City.

Some 150 combinations of water level hydrographs for the Mekong at Sop Kok and discharge hydrographs of the Nam Mae Kok at mouth will be required for flood simulation near the river mouth as input to the Monte Carlo technique to establish the flood maps of required return periods.

Flood damages and flood risk

Flood damages have been assessed through a data collection and social surveys in 12 communes. Results show that damages have decreased considerably over the past years, likely as a result of the flood control measures that have been implemented in the area at Chiang Rai, but it is also possible that lower floods occurred in the past years. A proper risk assessment could not be established due to issues with the hydraulic model that makes it unsuitable for simulations at this point in time. Flood damage probability curves are presented but should be interpreted with great caution because these are indicative only, due to lack of hydraulic simulation results.

However, the methodologies applied to arrive at flood risk assessment have been presented in the report and are based on the Best Practice Guidelines for Flood Risk Assessment (Volume 3A).

In view of the specific interest expressed by TNMC, in addition to the methodologies applied for flood risk assessment, in an attachment to Part B of this report, methods for the state of the art economic valuation of loss of life has been incorporated.

How to proceed with flood risk assessment for the Nam Mae Kok Basin?

The flood risk assessment for the Nam Mae Kok should continue. Activities that are required comprise:

1. Improvements to the ISIS model for the Nam Mae Kok Basin; the model needs to be brought up to date with regard to the cross sections and needs to be recalibrated and validated. Also instability issues have to be addressed, likely by changing computation control parameter settings. It is advised that MRCS' IKMP modelling team assists TNMC in model improvements.

2. Once the improved model is available, the flood hazard assessment should be undertaken according to the very specific methodology as outlined in detail in Part A of this report and in Volume 3A, Best Practice Guidelines on Flood Risk Assessment.

3. Once the flood hazard has been established, the flood risk can be assessed with the flood damage data as presented in Part B of this report.

4. A complicating factor in the flood risk assessment for the Nam Mae Kok Basin is that the flood damage data come from a period when flood protection measures were being implemented which of course reduce damages already. Therefore it is recommended to continue data collection as per the methodology presented in this report and in the BPG.

5. It should then be possible to do the flood risk assessment for distinctive periods: before and after the implementation of the flood protection measures. This allows an analysis of the effectiveness of the measures taken and an assessment of the need for further measures.

This report is presented in two distinct parts, **Part A** presents the **Flood Hazard Assessment** and **Part B** presents the **Flood Damage and Flood Risk Assessment and the Social Dimensions of Flooding** as perceived by the local population.

Background

In the Stage 1 Workshop of the Component 2 of the Flood Management and Mitigation Programme (FMMP-C2), held in Ho Chi Minh City, Viet Nam, on 25 September 2008, it was agreed that the assessment of flood risks in the Lower Nam Mae Kok Basin in Thailand will be one of the Demonstration Projects (DPs) during the Stage 2 Implementation of the FMMP-C2.

The scope of this project was presented in the Workshop as follows:

1. The results of the socio-economic surveys will be used for the elaboration of damage curves for the urban and rural districts in the Province;

2. Hazard maps will be prepared with the help of hydraulic model under preparation;

3. Flood risk maps will be prepared;

4. Measures for flood risk reduction will be formulated.

Regarding the implementation of this project it was agreed that a "Working-group" will be established that will have a dual function, i.e.

1. Provide guidance to the FMMP-C2 consultants in the implementation of the Demonstration Project, especially regarding policy, strategy and institutional issues.

2. Participate in technical sessions that allow for the transfer of technology from the side of the consultants to the technical working-group members.

The Demonstration Projects are also meant to apply Best Practice Guidelines (BPGs) that are developed under the FMMP-C2. The following Best Practice Guidelines are intended to be used in the implementation of this Demonstration Project:

1. Guidelines for Flood Risk Assessment;
2. Guidelines for IFRM Planning and Impact Evaluation.

Guide to the reporting structure of the Flood Management and Mitigation Programme - Component 2, Structural Measures and Flood Proofing

Component 2 on Structural Measures and Flood Proofing of the Mekong River Commission's Flood Management and Mitigation Programme was implemented from September 2007 till January 2010 under a consultancy services contract between MRCS and Royal Haskoning in association with Deltares and UNESCO-IHE. The Implementation was in three Stages, an Inception Phase, and two implementation Stages. During each stage a series of outputs were delivered and discussed with the MRC, the National Mekong Committees and line agencies of the four MRC member countries. A part of Component 2 - on 'Roads and Floods' - was implemented by the Delft Cluster under a separate contract with MRC.

The consultancy services contract for Component 2 specifies in general terms that, in addition to a Final Report, four main products are to be delivered. Hence, the reports produced at the end of Component 2 are structured as follows:

Volume 1	**Final Report**
Volume 2	**Characteristics of Flooding in the Lower Mekong Basin:**
Volume 2A	*Hydrological and Flood Hazard in the Lower Mekong Basin;*
Volume 2B	*Hydrological and Flood Hazard in Focal Areas;*
Volume 2C	*Flood Damages, Benefits and Flood Risk in Focal Areas, and*
Volume 2D	*Strategic Directions for Integrated Flood Risk Management in Focal Areas.*
Volume 3	**Best Practice Guidelines for Integrated Flood Risk Management**
Volume 3A	*Best Practice Guidelines for Flood Risk Assessment;*
Volume 3B	*Best Practice Guidelines for Integrated Flood Risk Management Planning and Impact Evaluation;*
Volume 3C	*Best Practice Guidelines for Structural Measures and Flood Proofing;*
Volume 3D	*Best Practice Guidelines for Integrated Flood Risk Management in Basin Development Planning, and*
Volume 3E	*Best Practice Guidelines for the Integrated Planning and Design of Economically Sound and Environmentally Friendly Roads in the Mekong Floodplains of Cambodia and Vietnam[1].*
Volume 4	**Project Development and Implementation Plan**
Volume 5	**Capacity Building and Training**
Volume 6	**Demonstration Projects**
Volume 6A	*Flood Risk Assessment in the Nam Mae Kok Basin, Thailand;*
Volume 6B	*Integrated Flood Risk Management Plan for the Lower Xe Bang Fai Basin, Lao PDR;*
Volume 6C	*Integrated Flood Risk Management Plan for the West Bassac area, Cambodia;*
Volume 6D	*Flood Protection Criteria for the Mekong Delta, Viet Nam;*
Volume 6E	*Flood Risk Management in the Border Zone between Cambodia and Viet Nam.*

The underlying report is **Volume 6A** of the above series.

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[1] Developed by the Delft Cluster

The FMMP Component 2, Structural Measures and Flood Proofing, was developed in three steps: the Inception Phase and Stages 1 and 2 of the Implementation Phase. The Inception Phase began at the end of September 2007 and concluded in accordance with the Terms of Reference with a Regional Workshop in Ho Chi Minh City at the end of January 2008, only 4 months after project initiation. The original TOR envisaged the Stage 1 Implementation Phase to be carried out in a period of 6 months, leaving 12 months for the Stage 2 Implementation Phase. See for reference *Final Report*, Volume 1.

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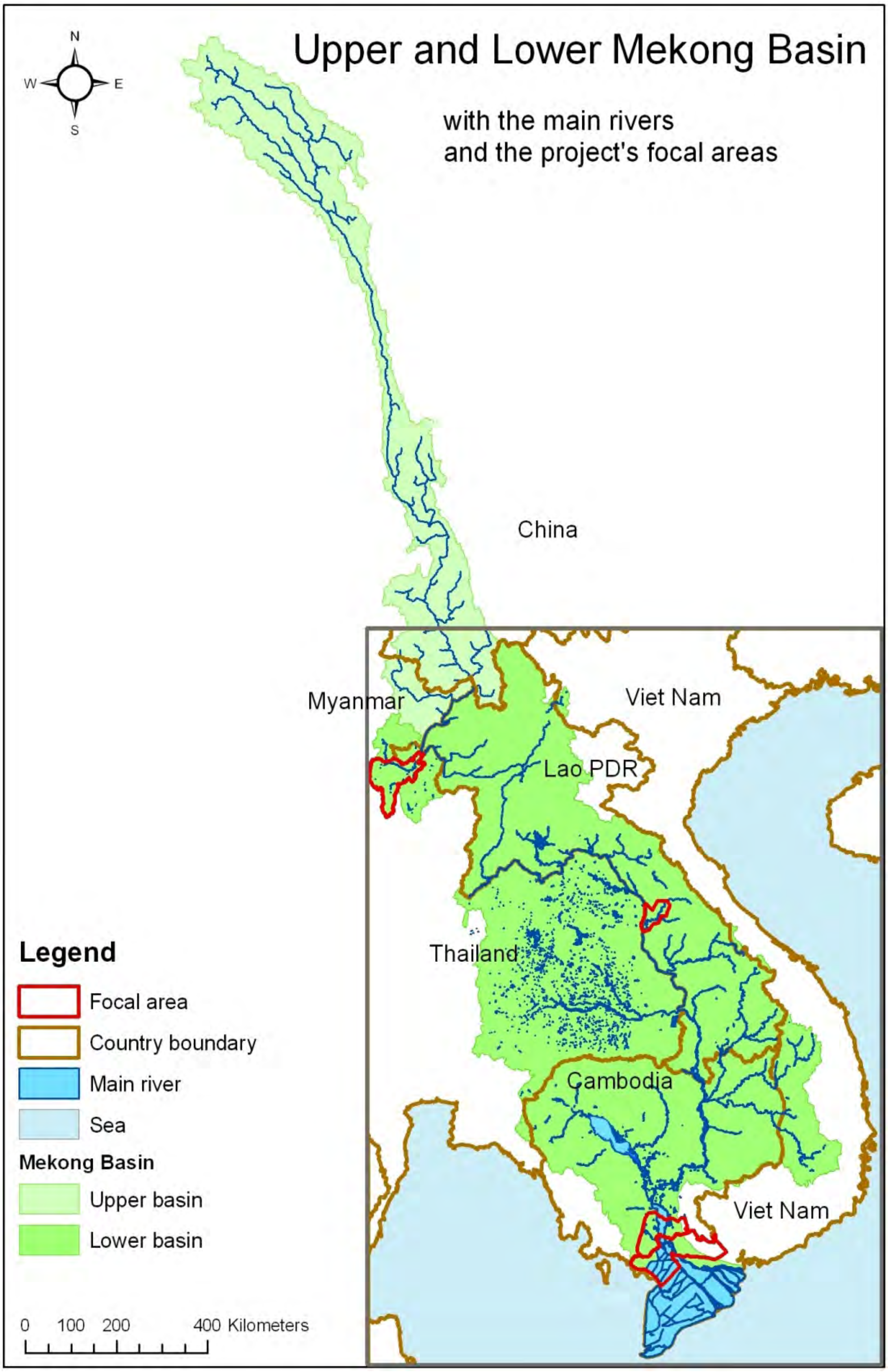
Upper and Lower Mekong Basin
with the main rivers
and the project's focal areas
N
W
E
S
China
Myanmar
Viet Nam
Lao PDR
Thailand
Cambodia
Viet Nam
Legend
Focal area
Country boundary
Main river
Sea
Mekong Basin
Upper basin
Lower basin
0 100 200 400 Kilometers

ABBREVIATIONS AND ACRONYMS

ADB	Asian Development Bank
amsl	above mean sea level
BDP	Basin Development Planning Programme (MRC)
DEM	Digital Elevation Model
DSF	Decision Support Framework
DTM	Digital Terrain Model
DWR	Department of Water Resources of Thailand
EIA	Environmental Impact Assessment
EV1	Extreme Value type 1 distribution (hydrology)
FGD	Focal Group Discussion
FMM	Flood Management and Mitigation
FMMP	Flood Management and Mitigation Programme (MRC)
FMMP-C1	Component 1 of the MRC FMMP: Establishment of the Flood Management and Mitigation Centre (RFMMC)
FMMP-C2	Component 2 of the MRC FMMP: Structural Measures and Flood Proofing
FMMP-C3	Component 3 of MRC FMMP: Enhancing Cooperation in Addressing Transboundary Flood Issues
FMMP-C4	Component 4 of the MRC FMMP: Flood Emergency Management Strengthening
FMMP-C5	Component 5 of the MRC FMMP: Land Management
FRM	Flood Risk Management
GEV	Generalised Extreme value
GIS	Geographic Information System
IFRM	Integrated Flood Risk Management
IKMP	Information and Knowledge Management Programme (MRC)
ISIS	Hydrodynamic simulator for modelling of flows and levels for channels and estuaries, used by MRC
IWRM	Integrated Water Resources Management
LMB	Lower Mekong Basin
MRC	Mekong River Commission
MRCS	Mekong River Commission Secretariat
NGO	Non-Governmental Organisation
NMC	National Mekong Committee
POR	Plain of Reed
PR	Provincial Road
ProDIP	Project Development and Implementation Plan
RNE	Royal Netherlands Embassy
TCEV	Two Component Extreme Value
THB	Thai Baht, currency of Thailand
TOR	Terms of Reference
USD	United States Dollar
WUP	Water Utilization Programme of MRC
WUP-A	WUP Basin Modelling and Knowledge Base Project
WWF	World Wildlife Fund
1D/2D/3D	One Dimensional/Two Dimensional/Three Dimensional

GLOSSARY

Damage curve	The functional relation between inundation characteristics (depth, duration, flow velocity) and damage for a certain category of elements at risk.
Direct damage	All harm which relates to the immediate physical contact of flood water to people, property and the environment. This includes, for example, damage to buildings, economic assets, loss of standing crops and livestock, loss of human life, immediate health impacts and loss of ecological goods.
Double rice	Rice from a cropping system, where 50% of the rice straw from the early-rice was assumed to be incorporated into soils of the late rice season.
Exposure	The people, assets and activities that are threatened by a flood hazard.
Flood control	A structural intervention to reduce the flood hazard.
Flood damage	Damage to people, property and the environment caused by a flood. This damage refers to direct as well as indirect damage.
Flood damage risk (= Flood risk)	The combination or product of the probability of the flood hazard and the possible damage that it may cause. This risk can also be expressed as the *average annual possible damage*.
Flood hazard	A flood that *potentially may* result in damage. A hazard does not necessarily lead to damage.
Flood hazard map	Map with the predicted or documented extent/depth/velocity of flooding with an indication of the flood probability.
Flood proofing	A process for preventing or reducing flood damages to infrastructural works, buildings and/or the contents of buildings located in flood hazard areas.
Flood risk management	Comprehensive activity involving risk analysis, and identification and implementation of risk mitigation measures.
Flood risk management measures	Actions that are taken to reduce the probability of flooding or the possible damages due to flooding or both.
Flood risk map	Map with the predicted extent of different levels/classes of *average annual possible damage.*
Hydrological hazard	A hydrological event (discharge) that may result in flooding.
Indirect damage	All damage which relate to the disruption of economic activity and services due to flooding.

Integrated flood risk management	The approach to Flood Risk Management that embraces the full chain of a meteorological hazard leading to flood damages and considers combinations of structural and non-structural solutions to reduce that damage.
Meteorological hazard	A meteorological event (storm) that may result in a hydrological hazard and, eventually, in flooding.
Resilience	The ability of a system/community/society to cope with the damaging effect of floods.
Susceptibility	The opposite of resilience, that is to say the inability of a system/community/society to cope with the damaging effect of floods.
Vulnerability	The potential damage that flooding may cause to people, property and the environment.

PART A

FLOOD HAZARD ASSESSMENT

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

Part A deals with flood hazard assessment for the Nam Mae Kok. Tributary floods in the Chiang Rai region cause flooding in parts of the city and in the agricultural area south of the city. In the vicinity of the Mekong near the Nam Mae Kok mouth flooding is caused by large discharges from the Nam Mae Kok backed up by high stages in the Mekong. The general procedure used in both cases is presented and its application to the Nam Mae Kok is discussed.

The setup of this report is as follows. The procedure for flood hazard assessment for tributary and combined floods is outlined in Chapter 2. A description of the Nam Mae Kok Basin, its hydraulic infrastructure, hydrological monitoring system and data availability is given in Chapter 3. The hydrological hazard is elaborated in Chapter 4. The hydraulic model for the simulation of the floods on the Nam Mae Kok and applied boundary conditions is presented in Chapter 5. Conclusions on the hydrological hazard analyses are drawn in Chapter 6.

CHAPTER 2

FLOOD HAZARD ASSESSMENT PROCEDURES

2 FLOOD HAZARD ASSESSMENT PROCEDURES

2.1 General

The procedure for flood hazard assessment in case of tributary and combined floods is discussed in this chapter. It deals with the computation of flood level elevations and flood extent of selected return periods and the depth and duration of flooding. Subsequently, flooding depth and duration are combined with land use information to determine the losses and benefits (social, environmental and economic) of the flooding, which is discussed in a separate volume.

2.2 Outline of procedures

2.2.1 Tributary floods

Tributary floods refer to floods on tributaries of the Mekong but not affected by backwater from the Mekong. These floods are of limited duration caused by extreme discharge in the tributaries. When a homogeneous discharge series of sufficient length (> 15 years) is available for the concerned river reach the hydrological hazard can be derived from statistical analysis of annual flood peaks and flood volumes and their interrelation. A hydraulic model of river and floodplain is subsequently used for the transformation of hydrological hazard into flood hazard. A selection of representative flood hydrographs, covering the full spectre of flood peaks and flood volumes, are transformed into water levels using the hydraulic model. The levels and flood volumes are input to a Monte Carlo procedure to derive the frequency of occurrence of water levels as a function of time and space. Comparing the levels for selected frequencies with a DEM flood hazard maps can be created.

Reference is made to the Flood Hazard Assessment Guidelines, Volume 3A in the series, for a full description of the procedure.

2.2.2 Combined floods

The flood hazard of combined floods also uses the Monte Carlo sampling technique to derive exceedance probabilities of water levels and damages. The procedure uses three random variables, representing the main causes for high water levels in the downstream part of the Nam Mae Kok:

- The maximum discharge in the Mekong River at Chiang Saen;
- The total volume of the flow in the Mekong River at Chiang Saen;
- The maximum discharge in the Nam Mae Kok near the river mouth.

The first two variables determine the downstream water level in the Mekong and the last one the upstream inflow to the Nam Mae Kok River reach at mouth. For each of the three random variables, samples are taken from their respective probability distribution functions. This procedure is repeated *N* times (with *N* sufficiently large) to obtain *N* combinations of possible realisations of the three random variables. This can be considered as a synthetic series of *N* years, where each sampled combination of random variables describes the main hydraulic features of the flood season in a single year.

For each combination/year the hydraulic model is applied to derive the relevant hydraulic features like maximum water level at a number of locations in the Nam Mae Kok. Formally, this means the hydraulic model should be run *N* times, but since *N* is generally quit large, that would require such a long computation time that the procedure would become unpractical. Instead, the model is run for 150 different combinations of the three random variables that basically cover the whole spectre of possible outcomes. The results of the 150 simulations are stored in a database. Results of the *N* Monte Carlo runs are then determined by interpolation of the results of the 150 simulations. Since 3 random variables are involved, the interpolation is 3-dimensional.

Reference is made to the Flood Hazard Assessment Guidelines for a full description of the procedure.

CHAPTER 3

BASIN DESCRIPTION

3 BASIN DESCRIPTION

3.1 General

The Nam Mae Kok Basin has been selected by the TNMC for Integrated Flood Risk Management. The area concerns the Nam Mae Kok River from Chiang Rai to its confluence with the Mekong just downstream of Chiang Saen at rkm 2,359.

3.2 Basin description

The Nam Mae Kok Basin (see Figure 3-1) covers an area of 10,730 km2. The length of the river from source to mouth is 320 km. The river begins in Myanmar and crosses the Thai border after 170 km near Ban Tha Ton. In Thailand the river is joined by the Nam Mae Fang near to Thai-Myanmar border, at Chiang Rai upstream of the Chiang Rai Weir by the small but for flooding important Nam Mae Korn, and just downstream of the weir by the largest tributary the Nam Mae Lao. From Chiang Rai to the river mouth a few smaller tributaries like the Mae Hang and Mae Phue join before the Kok drains into the Mekong at Sop Kok, some 5 km downstream of Chiang Saen gauging station at an elevation of 355 m amsl. The basin is mountainous on the divides with elevations up to 2,000 m, see Figure 3-1.

The valleys of the Fang, the Lao and the Kok rivers from Chiang Rai to the mouth are flat and flood prone, see Figure 3-3. The confluence of the Kok River with Mekong River is shown in Figure 3-4.

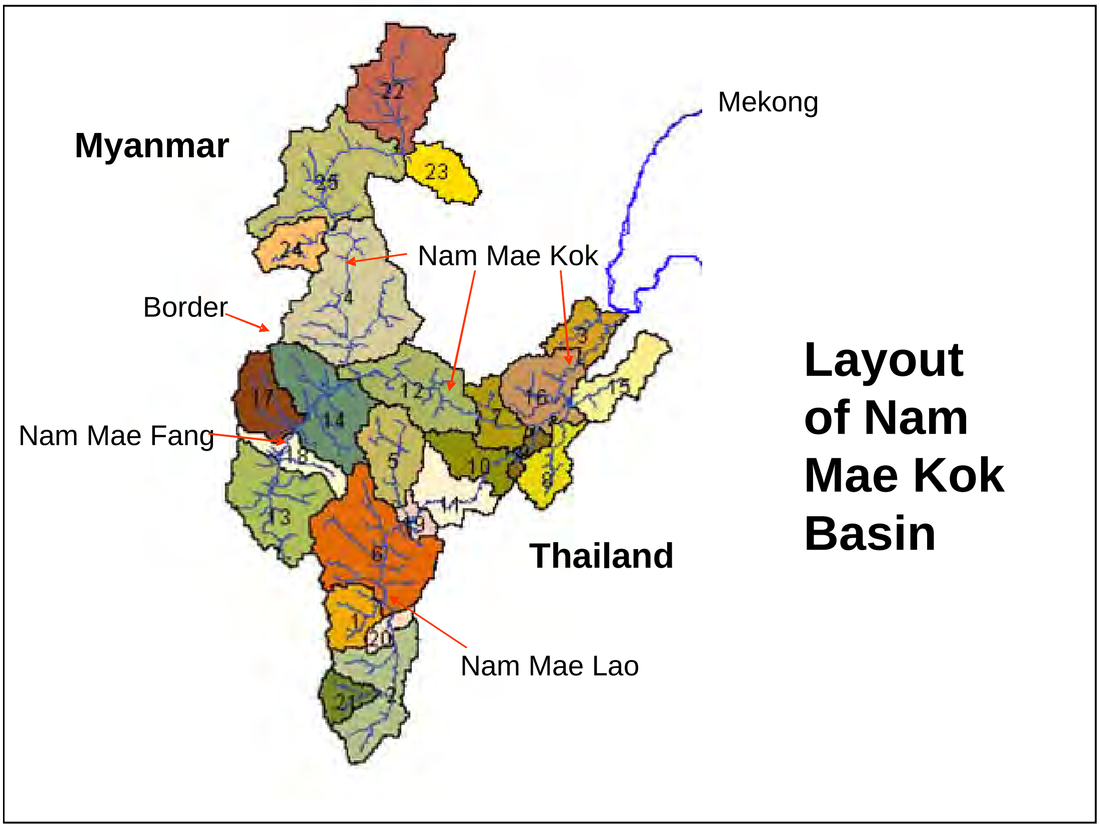

Figure 3-1 Layout of Nam Mae Kok Basin.

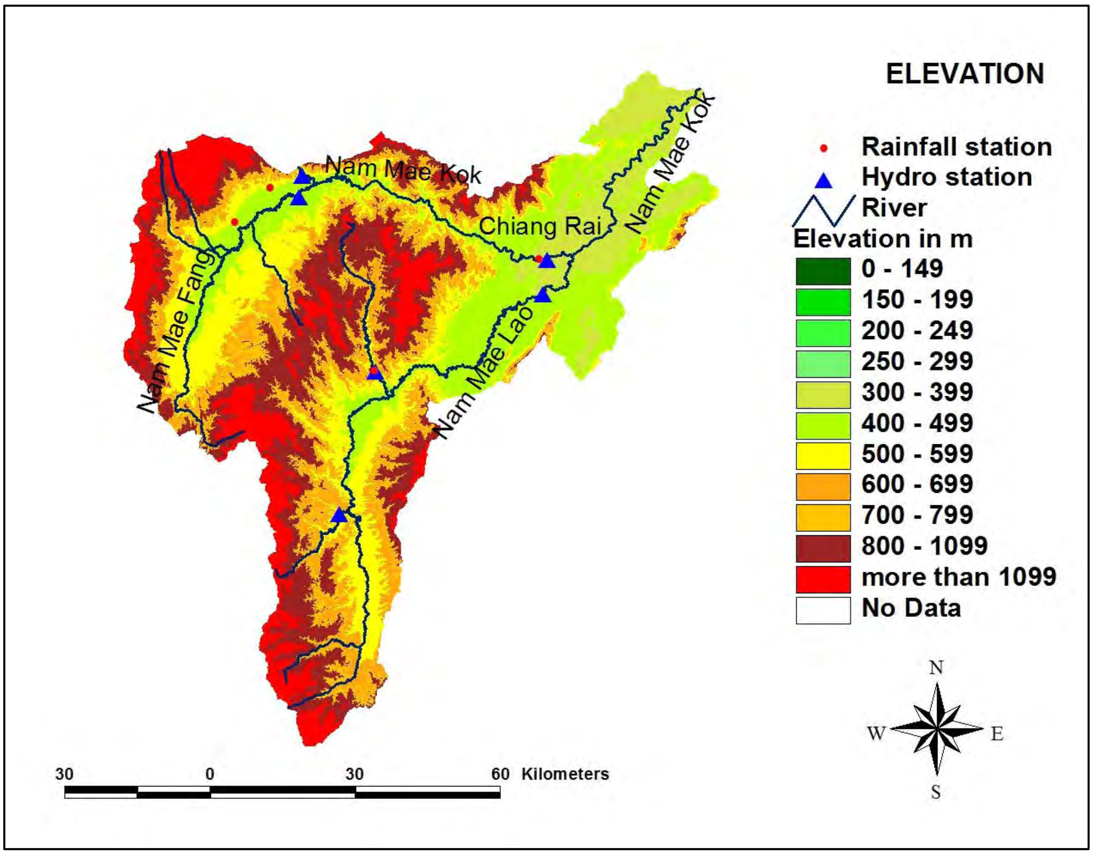

Figure 3-2 Nam Mae Kok elevation map.

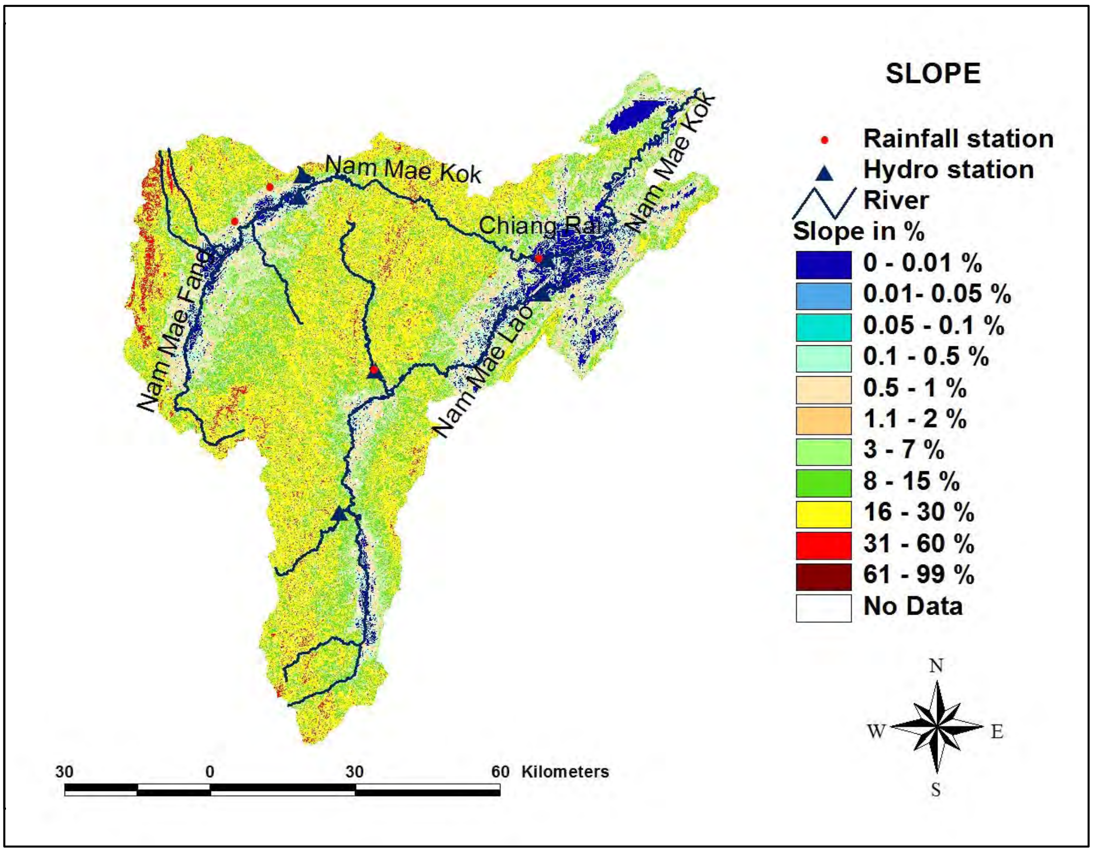

Figure 3-3 Nam Mae Kok slope map.

Figure 3-4 Confluence of Nam Mae Kok with Mekong, 7 km d/s of Chiang Saen.

Some 31% of the total basin area of the Nam Mae Kok is located in Myanmar. The first major tributary in Thailand, the Fang, with a length of 120 km drains 18% of the Kok Basin. At Chiang Rai Bridge above the mouth of Korn and Lao rivers the basin area amounts 6,133 km2 (see Table 3-1). The 37 km long Nam Mae Korn drains only 162 km2, whereas the Nam Mae Lao with a length of 190 km discharges a runoff of 3,115 km^2, or 29% of the total area. At the confluence of the Nam Mae Lao, just downstream of the Chiang Rai Weir, the Kok conveys the flow of some 88% of the basin.

Table 3-1 Catchment areas in Nam Mae Kok Basin according to SWAT (note that the areas differ slightly from those presented in the MRC yearbooks).

Location	**Area (km^2)**
Kok at Ban Pong Na Kham	5,890.4
Kok at Chiang Rai	6,133.4
Nam Mae Korn	162.0
Lao at Ban Pong Pu Fuang	2,584.8
Lao at mouth	3,115.1
Kok d/s Lao confluence	9,410.5
Kok at Ban Mae Phaeng	10,475.2
Kok at mouth	10,730.1

The soils in the Nam Mae Kok Basin belong mainly (88%) to the Hydrologic Soil Group B with a soil composition of 21% clay, 24% silt and 55% sand (MRC soil codes Ao, Nh and SC). Some 70% of the basin area is covered with forest found in the upper areas. Agriculture has developed in the lower reaches covering some 18% of the basin.

The natural river regime has been modified by irrigation water use and storage for hydropower. According to BDP (2006) in 1998 in the basins of the Kok and adjacent Ing together, about 150,000 ha were irrigated in the wet season and some 15,000 ha in the dry season. Irrigation water requirement for 2000 was estimated at 770 MCM, whereas the needs for domestic and industrial water supply amounted 31 MCM. Some 8 reservoirs are planned, to achieve an expansion of 30% of the irrigated area in the Kok Basin. These projects will at least partly be multipurpose, combining irrigation water supply and hydropower production. The present and planned hydropower projects in the Nam Mae Kok Basin affecting the flow regime are presented in Table 3-4. The present storage capacity is seen to be very small compared to the annual Kok flow of about 5.24 BCM. However, with the Nam Kok hydropower dam implemented in Myanmar (at present at pre-feasibility status) some 30% of the flow in the Nam Mae Kok can be fully controlled as the storage capacity will be large (about 60% of the annual river flow at mouth).

Table 3-2 Existing and planned hydropower projects in Kok Basin (source BDP, 2006).

Existing

Project	Capacity (MW)	Storage (MCM)
Nam Mae Mao	4.6	20
Mae Chai, Mae Kum Luang	7.2	0
Chiang Rai Weir on Nam Mae Kok	-	1.3

Planned

Project	Storage (MCM)
Nam Kok hydropower dam (Myanmar)	3,033
Fang sub-basin (3 reservoirs)	134
Lao sub-basin (4 reservoirs)	204
Total	**3,370**

3.3 Problem description

The major part of the city of Chiang Rai is enclosed by the Kok and Korn rivers. Expansion of the city is taking place north of Kok River and between the Korn and Lao rivers.

Flood prone areas in the Nam Mae Kok Basin are following (see also the slope map in Figure 3-3):

- Valley of Nam Mae Fang River;
- Chiang Rai Province; and
- Mouth of Nam Mae Kok River.

The possible flood extent in the lower part of the Kok Basin derived from hydraulic model calculations, is presented in Figure 3-5 (Kittipong, 2009). It shows flooding near the confluences of the tributaries in Chiang Rai and along the Kok River between Chiang Rai and the river mouth.

Floods around the city are generated either by the Kok, the Korn and/or by the Lao. The city is flood prone when the rivers convey large discharges. In the past, Chiang Rai City was mostly endangered by floods from the Lao and the Korn (see Figure 3-6). Water was spilling over from the Lao upstream of Chai Sombat Weir and entered the floodplain of the Korn, aggravating the flooding in Chiang Rai. To reduce the flooding the Chiang Rai Municipality and the Royal Irrigation Department implemented in 2005 a number of flood protection measures (see Figure 3-7), including:

- The Nam Mae Korn-Nam Kok Diversion Canal including intake and outlet weirs;

- Improvement of additional 4 weirs in the Nam Mae Korn;
- Improvement of Lao embankment upstream of Chai Sombat Weir over a distance of 15 km.

Annual maximum rivers discharges generally occur in the period July-November as can be observed from Table 3-3. In the period 1971-2007 the largest annual peak in the Kok upstream of Chiang Rai occurred in 1971. The hydrograph is shown in Figure 3-8. It shows a fairly rapidly rising and falling flood, lasting for about 1 week, which is characteristic for the floods in the Nam Mae Kok at Chiang Rai. The floods in the Nam Mae Lao generally have a shorter duration. Very recently, in 2005 (and also 2006), the Lao received one of its biggest floods, while the Korn was also extreme in that year, see Figure 3-9. The Lao peaked in 2005 two times, with values higher than the annual maximum of the other years.

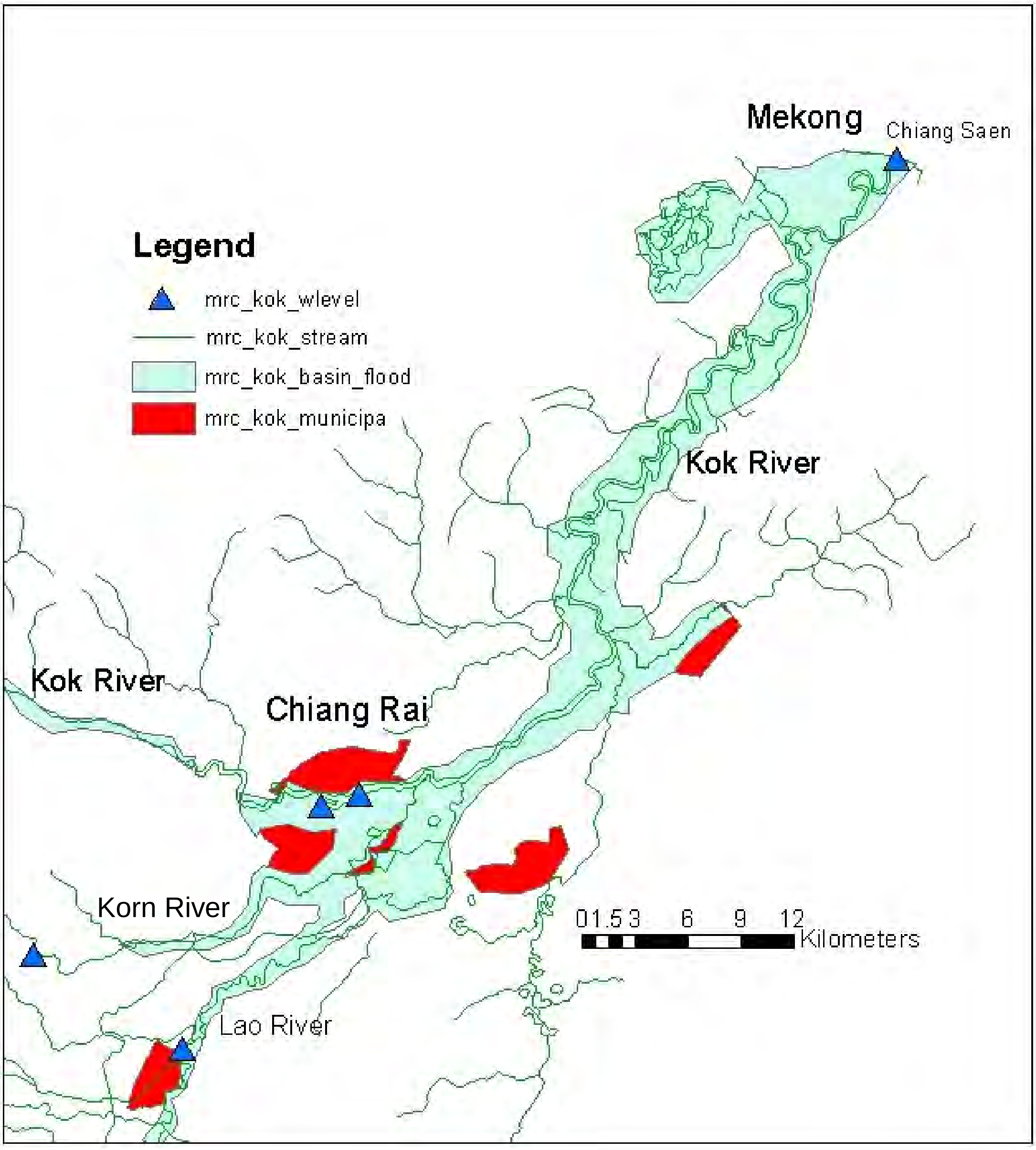

Figure 3-5 Flooding around Chiang Rai and along Lower Nam Mae Kok.

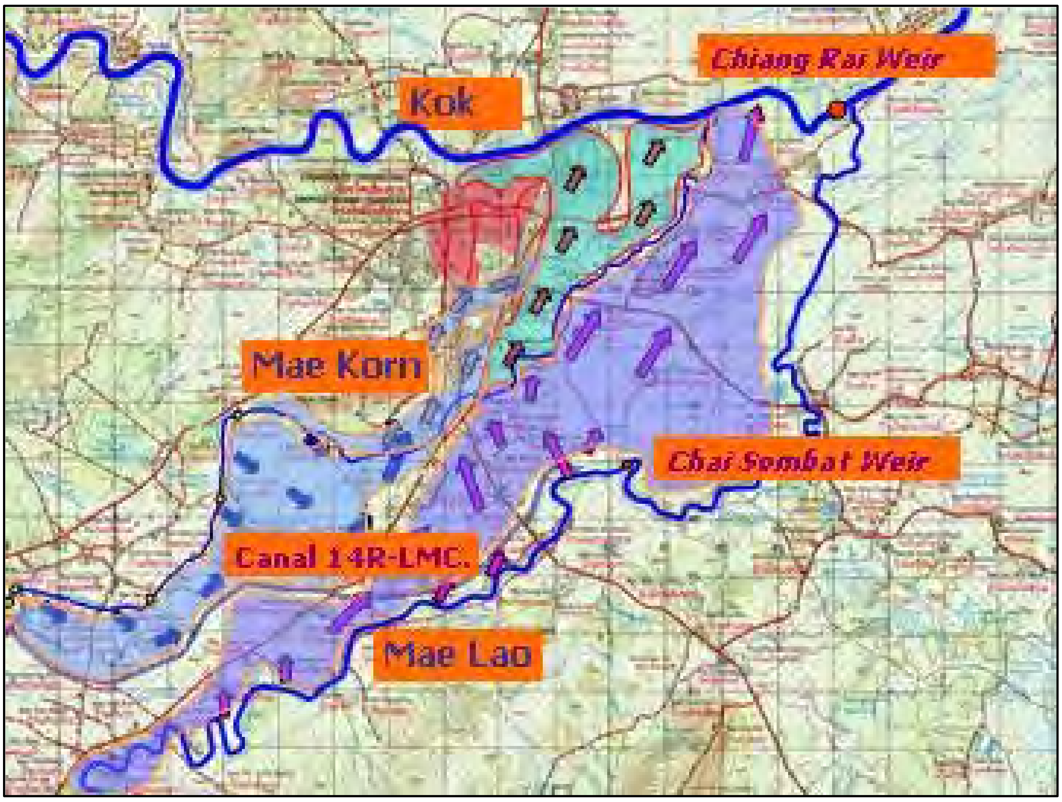

Figure 3-6 Flooding in Chiang Rai Province near the city of Chiang Rai.

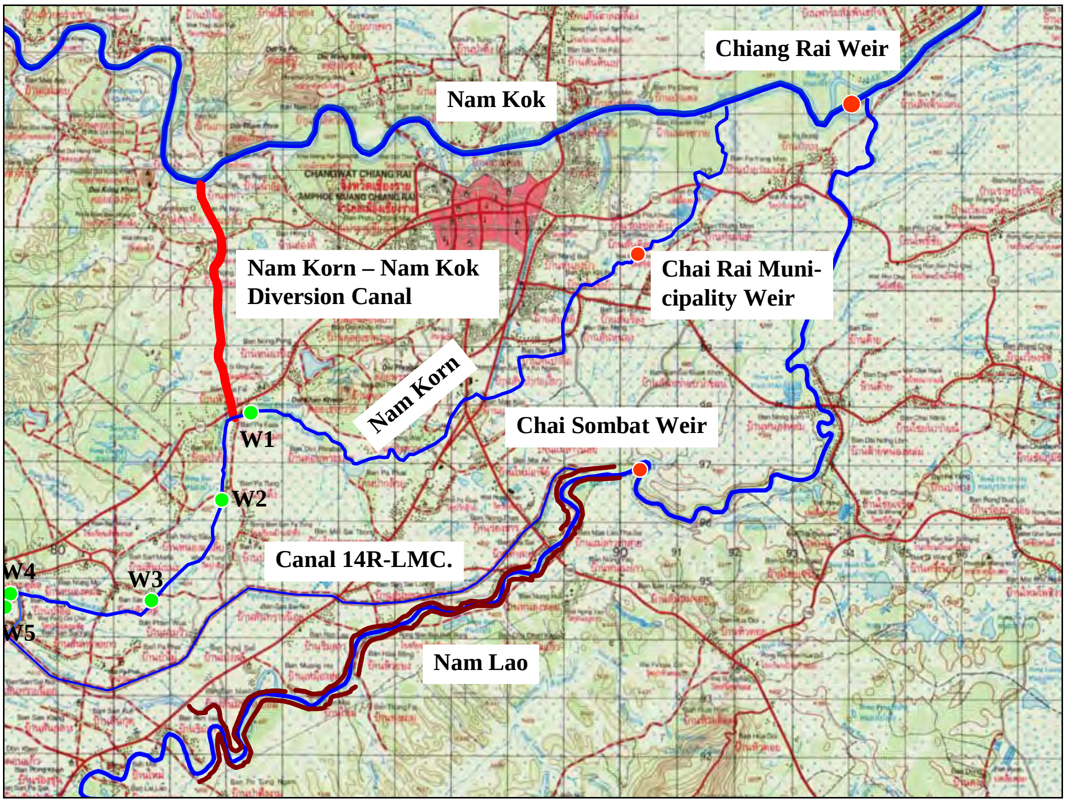

Figure 3-7 Flood mitigation measures around Chiang Rai, including a diversion canal from Korn to Kok, weirs in the Nam Mae Korn and embankments along the Lao u/s Chai Sombat Weir.

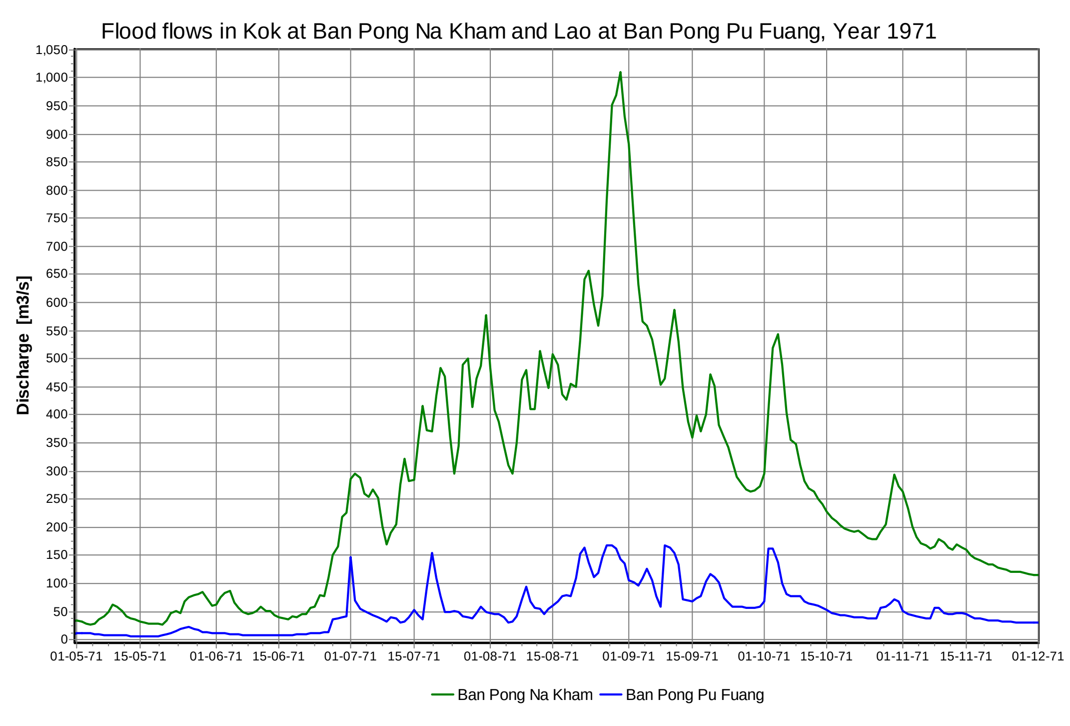

Figure 3-8 Flood of 1991 on Nam Mae Kok at Ban Pong Na Kham u/s of Chiang Rai and Nam Mae Lao at Ban Pong Pu Fuang.

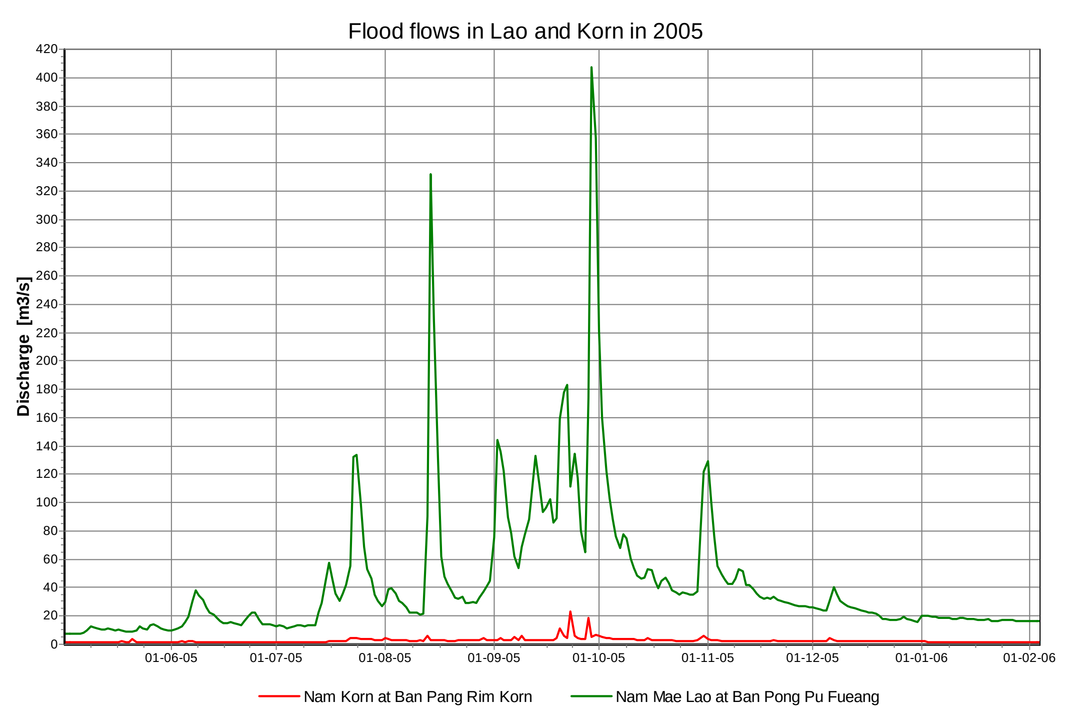

Figure 3-9 Floods of 2005 in Nam Mae Lao at Ban Pong Pu Fuang and Nam Mae Korn at G4.

Table 3-3 Summary of ranked annual flood peaks of the period 1971-2007 in the Kok at Ban Pong Na Kham and d/s Lao confluence and the Lao at Ban Pong Pu Fuang.

Nam Mae Kok at Ban Pong Na Kham				**Nam Mea Lao at Ban Pong Pu Fuang**				**Nam Mae Kok d/s Lao confluence**			
Year	**Month**	**Day**	**Q_{max} (m^3/s)**	**Year**	**Mnth**	**Day**	**Q_{max} ((m^3/s)**	**Year**	**Month**	**Day**	**Q_{max} (m^3/s)**
1971	8	30	1010	1973	9	21	515	1973	9	21	1266
1973	9	23	846	2005	9	29	407	1971	8	30	1233
1987	8	26	781	2006	9	24	313	1972	8	26	1133
2004	9	12	781	1994	9	1	304	1994	8	31	1113
1995	9	5	774	1972	8	26	277	1995	9	5	1099
1972	8	26	751	1980	9	3	254	2005	9	30	1098
1994	8	31	721	1975	9	23	252	1987	8	25	1060
1988	8	17	697	1987	8	24	248	2004	9	12	990
2005	10	1	661	2003	9	13	247	2003	9	13	949
1981	8	6	644	2002	9	10	234	1980	9	10	928
1980	9	10	614	1995	9	5	231	2006	9	23	867
2003	9	13	611	1976	9	27	222	1976	9	28	862
1976	9	28	561	1999	9	25	198	1988	8	17	830
1996	8	21	555	2001	8	6	186	1981	8	6	823
1983	9	16	546	2004	9	22	181	2001	8	6	796
2001	8	6	538	1988	6	7	180	1996	9	4	716
1982	8	20	531	1991	9	5	174	1983	9	16	714
2006	9	22	527	1974	8	19	173	1991	9	5	708
1999	9	1	506	1971	8	27	168	2002	9	10	705
1978	9	13	488	1984	9	6	167	1977	9	23	699
1997	9	3	485	1977	9	23	166	1975	9	24	687
1984	9	8	484	1978	7	4	164	1984	9	6	678
1977	9	23	469	1979	8	9	163	1978	9	13	637
1991	9	5	468	1997	9	29	156	1982	8	20	604
1975	9	15	449	1985	11	17	155	1989	9	27	603
2007	9	6	448	1986	9	9	134	1974	8	19	595
1985	9	15	439	1996	9	4	128	2000	8	9	590
2000	8	10	438	1983	11	13	127	1999	9	1	584
1989	9	27	431	2000	8	9	126	1985	9	15	580
2002	8	7	421	2007	9	29	122	1997	9	3	567
1998	8	26	388	1989	9	27	122	2007	9	6	563
1974	8	20	371	1982	9	10	121	1979	8	9	541
1986	7	27	359	1981	8	6	120	1998	9	10	522
1979	8	7	355	1998	9	10	118	1986	7	27	480
1990	8	2	306	1992	9	19	87	1990	8	1	421
1993	9	12	298	1990	7	31	87	1993	9	12	360
1992	7	27	255	1993	9	21	75	1992	9	19	294

3.4 Hydrological data requirement

The flood risk is assessed for the Chiang Rai area along the Nam Mae Kok, which requires determination of the flood hazard for the environs of the city. The flood extent, depth and duration are determined for the following return periods: 2, 10, 25 and 100 years. The flood hazard follows from the hydrological hazard using a hydraulic model. The type of approach is dependent on the variables determining the flood levels. In the upper and middle part the river discharge and downstream conveyance capacity are of importance. Near the river mouth an additional variable is involved due to backwater from the Mekong River. An estimate of the distance over which the effect of the Mekong River is felt on the flood levels in the Nam Mae Kok can be derived from a first order backwater calculation (see also Figure 3-10 for a definition sketch):

$$\Delta h_L \approx \Delta h_0 \exp\left(\frac{-3S_0 L}{h_e(1-Fr^2)}\right); \quad hence: \ln\left(\frac{\Delta h_L}{\Delta h_0}\right) \approx \frac{-3S_0 L}{h_e} \quad for\ Fr << 1;$$

$$at\ \Delta h_L = 5\%\ of\ \Delta h_0 \quad then \quad \ln\left(\frac{\Delta h_L}{\Delta h_0}\right) = -3, \quad so:$$

$$L_{5\%} = \frac{h_e}{S_0} \quad with: \quad h_e = 9\,m\ and\ S_0 = 4.34x10^{-4}\,, \quad it\ follows: \tag{3.1}$$

$$L_{5\%} = \frac{h_e}{S_0} = \frac{9}{4.34x10^{-4}} = 20{,}743\,m \approx 21\,km$$

with:

Δh_0 = deviation from equilibrium depth at x=0
Δh_L = deviation from equilibrium depth at x = L
h_e = equilibrium depth
S_0 = bed slope
Fr = Froude number

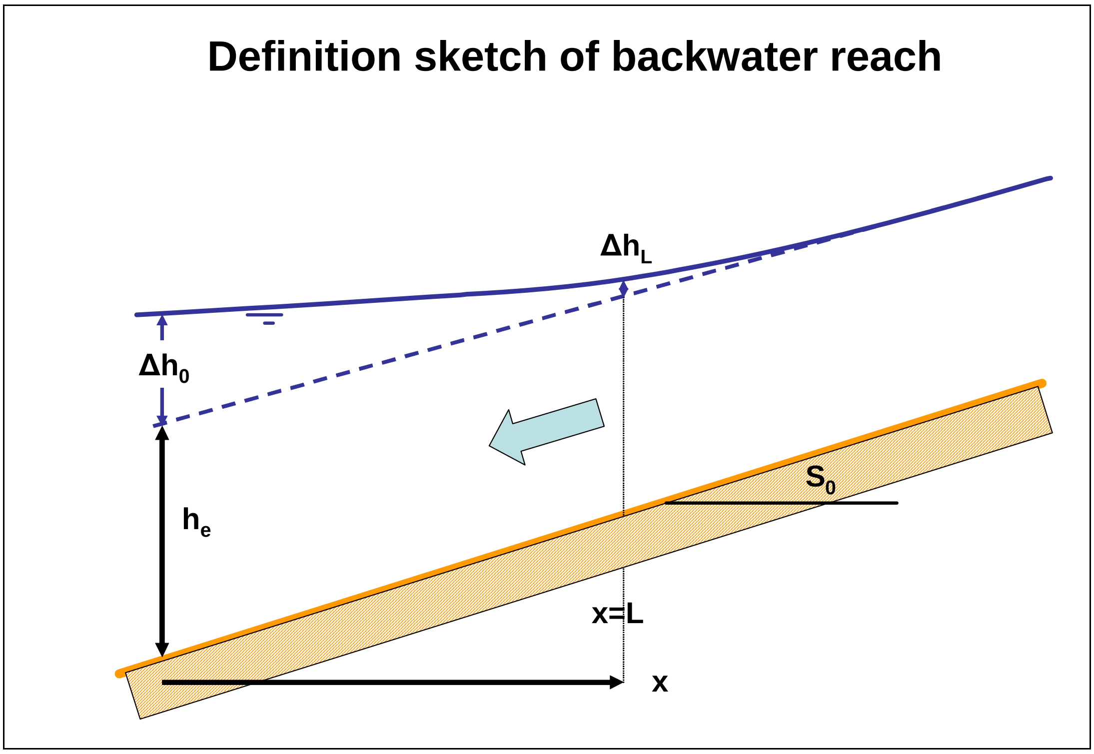

Figure 3-10 Definition sketch of extent of backwater reach.

In Figure 3-9 the equilibrium depth h_e is taken as the maximum observed water level reach at station Sop Kok on Mekong River at Nam Mae Kok mouth. The bed slope S_0 is derived from the gauge zero difference between station Chiang Rai (GZ = 387.85 m) distanced some 75 km from the mouth and station Sop Kok (GZ = 355.31 m). It follows that the effect of the Mekong practically vanishes at a distance of 21 km from the mouth. It implies that the flood hazard in the Chiang Rai region is only determined by the river flow, channel capacity and Chiang Rai Weir operation but not by the Mekong River. The comment in the Mekong Hydrological Yearbook e.g. of 1997 that the gauge at Chiang Rai is affected by backwater from the Mekong is therefore incorrect; it is affected by the weir, 5 km downstream of the station, near the confluence of the Nam Mae Lao, but not by the Mekong River.

The hydraulic model of the Nam Mae Kok extends from Ban Pong Na Kham on Kok, to Sop Kok at the mouth, including the Lao from Ban Pong Pu Fuang and the Korn from 14 km d/s of Ban Pang Rim Korn Hydrological Station (G4). The Mekong is included from Chiang Saen to Sop Kok.

For assessing the hydrological hazard and running the hydraulic model for flood risk assessment around Chiang Rai the following data is required:

- Discharge record for the Nam Mae Kok at Ban Pong Na Kham;
- Discharge record for the Nam Mae Lao at Ban Pong Pu Fuang;
- Discharge record for the Nam Mae Korn at 14 km d/s G4;
- Lateral inflow d/s of the upper model boundaries.

For risk assessment near the Nam Mae Kok mouth over its last 20-25 km the Mekong River stages and Kok River capacity in combination with the river flow determines the hydrological and flood hazard. This requires:

- Peak flows and flood volumes of the Mekong at Chiang Saen;
- A stage-discharge relation for the Mekong d/s Sop Kok;
- Peak flows and flood volumes in the Nam Mae Kok at the upper end of the backwater affected reach of the Kok;
- Lateral inflow d/s of the Kok boundary.

3.5 Hydrological network and data availability

Organizations that collect and use hydrological data of the Mekong Basin in Thailand are:

1. Department of Water Resources, Ministry of Natural Resources and Environment; responsible for hydrological and meteorological (mostly basic synoptic) stations; (variables are observed 5 times a day from 06.00 a.m. until 19.00 p.m.)
2. Royal Irrigation Department, Ministry of Agriculture and Cooperatives; responsible for hydrological stations.
3. Electricity Generating Authority of Thailand (EGAT); responsible for hydrological stations from hydropower dams.
4. Thai Meteorological Department, Ministry of Information, Communication and Technology; responsible for meteorological (full synoptic and climate) data and hydro-meteorological data, as national representative of World Meteorological Organization (WMO).

The hydrological network in the Nam Mae Kok Basin as available in the MRC HYMOS database is presented in

Table **3-4**. The gauges zeros of the water level gauging stations are given in Table 3-5. The locations of the discharge stations are shown in Figure 3-11.

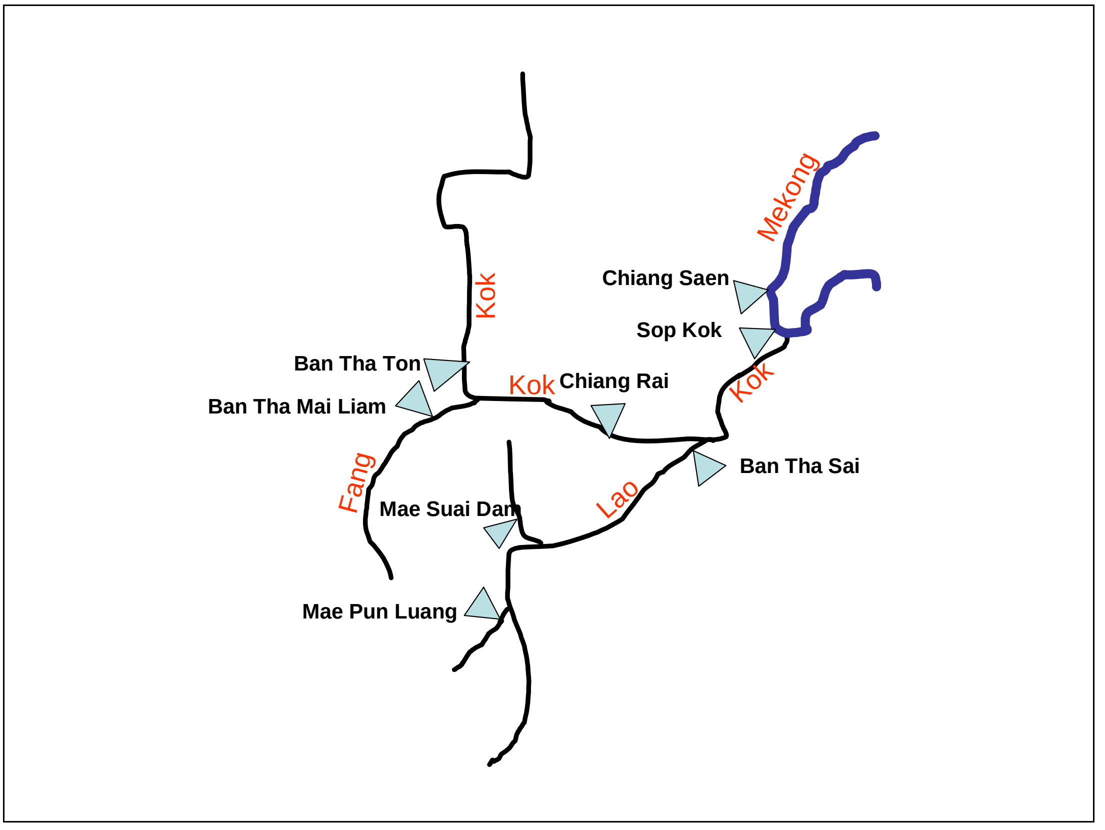

Figure 3-11 Location of discharge gauging stations in Nam Mae Kok Basin and on Mekong.

Table 3-4 Overview of rainfall, climatic and hydrometric stations in Nam Mae Kok with data availability.

Variable	Stations	ID	Long	Lat	Availability
Rainfall	Fang	199901	99.2334	19.9667	1953-72, 75-05
	Chiang Rai	199907	99.8334	19.9167	1963-2005
	Mae Suai Dam Site	199913	99.5167	19.7000	1980-2001
	Chiang Saen	200002	100.1000	20.2667	1966-2005-06
	Ban Mae AI	209902	99.3000	20.0334	1970-2005
Evaporation	Chiang Rai	199907	99.8334	19.9667	62-67,72-78,80-95,97-05
	Chiang Rai-FAO	-same-	-same-	-same-	from Climwat database
	Mae Suai Dam Site	199913	99.5167	19.9167	1981-2001
	Chiang Saen	200002	100.1000	19.7000	1976-2005
	Ban Mae AI	209902	99.3000	20.2667	1971-2005
Water level	Sop Ruak (rkm 2,372.4)	010401	100.0867	20.3484	1972-2005
	Chiang Saen (rkm 2,364)	010501	100.0834	20.2734	1960-2005
	Sop Kok (rkm 2,359)	010601	100.1333	20.2417	1972-1992
	Chiang Khong (rkm 2,313)	010801	100.4100	20.2684	1972-2005
	Ban Tha Ton on Nam Mae	050105	99.3634	20.0600	1969-2005
	Kok	050201	99.3584	20.0200	1969-2003
	Ban Tha Mai Liam on Fang	050104	99.8500	19.9184	1977-2005
	Chiang Rai on Nam Mae Kok	051001	99.5200	19.8534	1971-2001
	Dam Site on Nam Mae Suai	051101	99.4584	19.4334	1976-2003
	Dam Site on N. Mae Pun				
	Luang	050301	99.8434	19.8534	1970-2003
	Ban Tha Sai on Nam Mae Lao				
Discharge	Chiang Saen (rkm 2,364)	010501	100.0834	20.2734	1960-2006
	Sop Kok (rkm 2,359)	010601	100.1333	20.2417	1972-1987
	Ban Tha Ton on Nam Mae	050105	99.3634	20.0600	1969-2005
	Kok	050201	99.3584	20.0200	1969-2003
	Ban Tha Mai Liam on Fang	050104	99.8500	19.9184	1977-1993
	Chiang Rai on Nam Mae Kok	051001	99.5200	19.8534	1975-94, 96-99,
	Dam Site on Nam Mae Suai	051101	99.4584	19.4334	01
	Dam Site on N. Mae Pun				1976-2003
	Luang	050301	99.8434	19.8534	
	Ban Tha Sai on Nam Mae Lao				1972-2002

With respect to the gauge zeros of stations in the Nam Mae Kok, in the Mekong Hydrological Yearbooks (1960-1997) only for station Chiang Rai a change of 1.00 m in 1987 is mentioned.

Table 3-5 Gauge zero levels of water level gauging stations in and around Nam Mae Kok.

Station	ID	GZ (masl)	Area (km^2)
Sop Ruak (rkm 2,372.4)	010401	359.19	189,000
Chiang Saen (rkm 2,364)	010501	357.11	189,000
Sop Kok (rkm 2,359)	010601	355.31	203,825
Chiang Khong (rkm 2,313)	010801	341.96	211,000
Ban Tha Ton on Nam Mae Kok	050105	445.05	2,980
Ban Tha Mai Liam on Fang	050201	445.39	1,800
Chiang Rai on Nam Mae Kok	050104	387.85	6,060
Dam Site on Nam Mae Suai	051001	475.00	426
Dam Site on N. Mae Pun Luang	051101	455.64	258
Ban Tha Sai on Nam Mae Lao	050301	394.84	3,080$^{*)}$

(*) Note that the areas of the locations in the Kok Basin are slightly inconsistent with SWAT based areas presented in Table 3-1).

It is observed that the MRC Hydrological database includes only a very limited amount of the data needed for the assessment of the hydrological hazard and to run the hydraulic model. A first improvement on the data availability was obtained from the hydraulic model boundaries used by (Kittipong, 2009), available from 1985 onward. Additional data requirements were discussed with the TNMC. These data were received in late March 2009 including daily average levels and discharges at the model boundaries and instantaneous peak flow data. The data received via Kittipong and TNMC not available in the MRC database, is listed in Table 3-6.

Station Ban Pong Na Kham is located between the Kok-Fang confluence and Chiang Rai station. Ban Mae Phaeng was established on the Kok between Chiang Rai Weir and Sop Kok. Station Ban Pong Pu Fuang is located upstream of the weirs in the Nam Mae Lao. Reference is made to Table 3-1 for the catchment areas controlled by the stations.

Table 3-6 Overview of additional hydrological data of hydrometric stations in the Nam Mae Kok collected in 2009.

Station ID	**Station Name**	**River**	**Period of data availability (received)**			
by TNMC			**Q**	**Max-Min Q**	**H**	**Max-Min H**
030101	Ban Tha Ton	Nam Mae Kok	2006	1970-2005	2006-07	1970-2006
030102	Ban Pong Na Kham	Nam Mae Kok	1966-2008	1967-2005	1966-87, 1995-2007	1967-2006
030107	Ban Mae Phaeng	Nam Mae Kok	1994-2006	1994-2005	1994-2007	1994-2006
030201	Ban Tha Mai Liam	Nam Mae Fang	2004-06	1969-2005	2004-07	1969-2006
030301	Ban Tha Sai	Nam Mae Lao	2004-06	1971-2005	2004-07	1971-2006
030302	Ban Pong Pu Fuang	Nam Mae Lao	1971-2007	1971-2005	1970-2007	1971-2006
030401	Dam site	Nam Mae Suai	-	1971-2001		1971-2001
020102	Chiang Saen	Mekong	-		2006-07	
G4	Ban Pang Rim Korn	Nam Mae Korn				
-	5 Lateral inflows Kok	Nam Mae Kok	1985-2008			
-	3 Lateral inflow Lao	Nam Mae Lao	1985-2008			
-	2 Lateral inflow Korn	Nam Mae Korn	1985-2008			

3.6 Hydrological characteristics

3.6.1 Rainfall

The MRC database contains only the rainfall series in the Nam Mae Kok Basin and environs series for 5 stations. A denser network is available, but its data is not stored in the database.

Regarding validation, the available series have been subjected to double mass analysis and no anomalies were detected.

The annual and seasonal variations of the rainfall of selected stations in the basin are presented in Figure 3-12 and Figure 3-13. From the annual rainfall series it appears that around Chiang Rai-

Chiang Saen the rainfall is largest (1,700 mm per year) and lowest in the upper reaches of the Nam Mae Kok and in the Nam Mae Fang (1,300-1,400 mm per year). August is generally the month with the largest rainfall with on average 380 mm, followed by July and September, with respectively 320 and 280 mm.

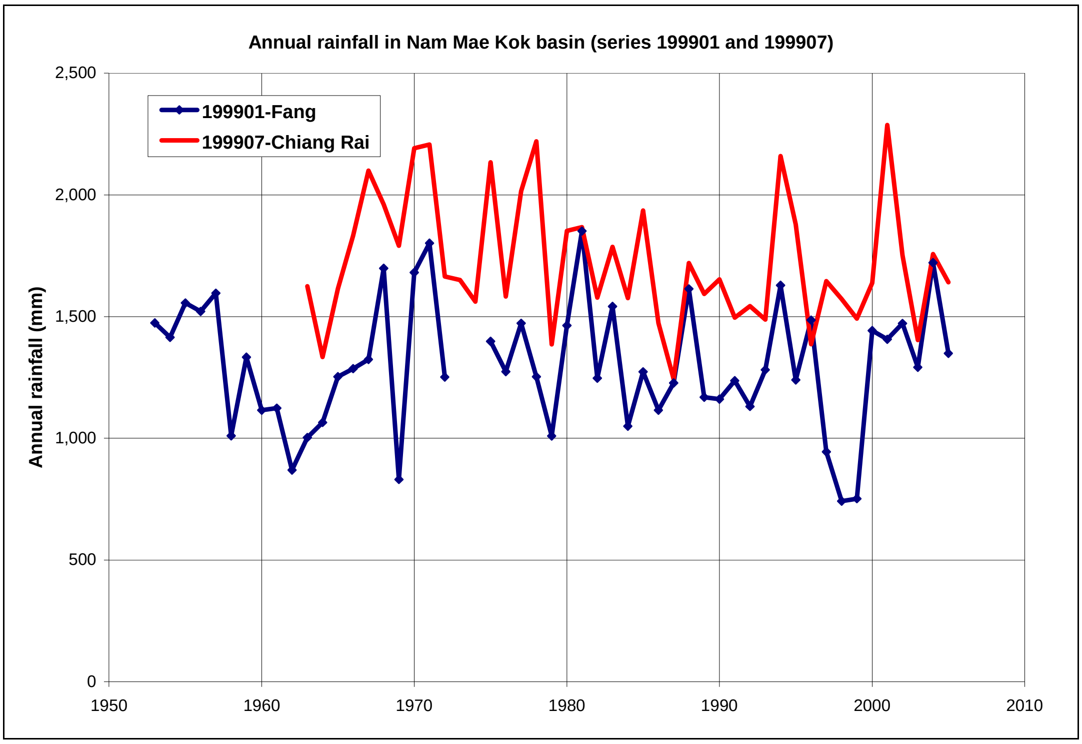

Figure 3-12 Annual rainfall in Nam Mae Kok Basin at Fang and Chiang Rai.

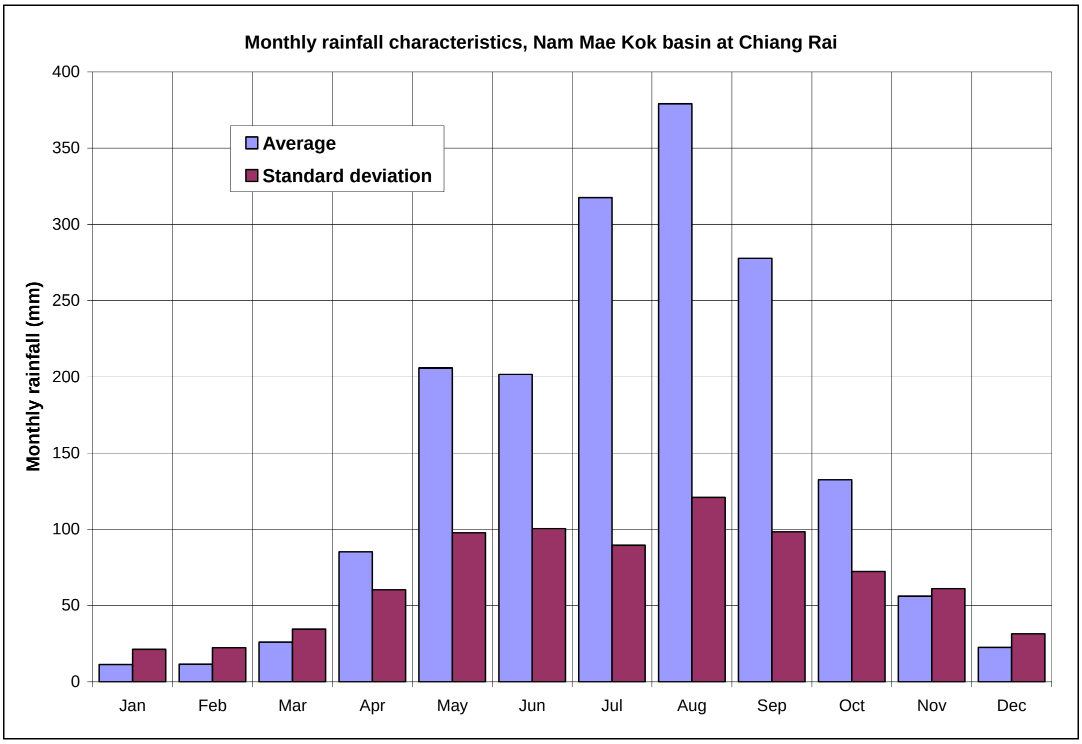

Figure 3-13 Statistics of monthly rainfall at Chiang Rai.

Statistics of annual maximum daily rainfall are summarised in Table 3-7 and Figure 3-14. Both EV1 (Gumbel) and GEV–distributions (see Chapter 4 for a description) fit to the annual maxima, with slightly higher values for EV1. According to the distributions the 10-year maximum daily rainfall is about 135 mm, and the 100-year daily rainfall ranges from 170 to 190 mm. Rainfall statistics of shorter duration will be required to evaluate and design the required capacity of the city's sewer system. For analysis of flooding from the river the river discharge and conveyance capacity is of importance.

Table 3-7 Parameters of EV1 and GEV distributions fitted to annual maximum daily rainfall at Chiang Rai and rainfall values for selected return periods.

Parameters		Return Period	Rainfall (mm)	
Type	Value	T (years)	EV1	GEV
EV1 α	21.4	2	95	97
u	87.2	5	119	121
GEV k	0.122	10	135	135
α	23.7	25	156	151
u	88.4	50	171	162
		100	186	172

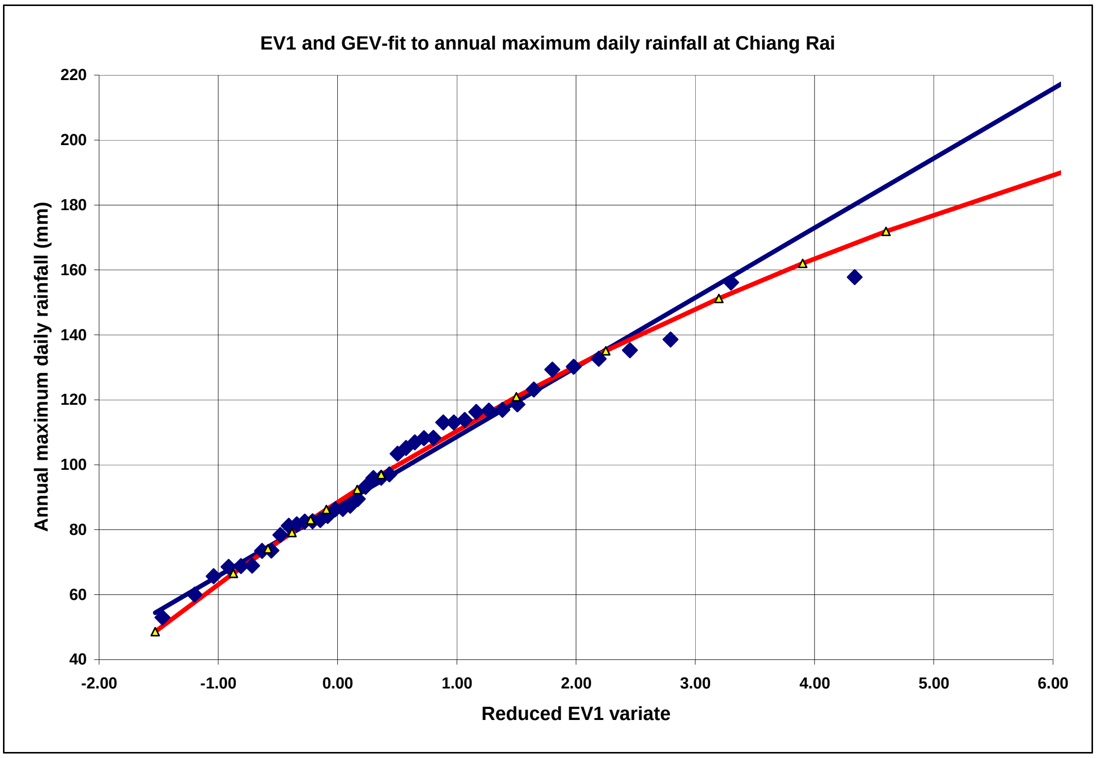

Figure 3-14 EV1 and GEV-fit to annual maximum daily rainfall at Chiang Rai, period 1963-2005.

3.6.2 Evaporation

Pan-evaporation data is available in the MRC database for 4 stations in the Nam Mae Kok Basin. Average annual totals range from 1330 mm to 1480 mm. FAO-Climwat database indicate annual totals of 1,370 mm for reference crop evaporation at Chiang Rai. Highest evaporation occurs in April-May, with about 5 mm/day.

The monthly evaporation data together with the average monthly rainfall for Chiang Rai is presented in Figure 3-15. It is observed that from May to October there is a large water surplus: the average rainfall exceeds the evaporation rate, but over the rest of the year there is a considerable deficit. It is also expected in view of the small storage capacity of the existing reservoirs and the large surplus in the wettest months that the present hydraulic infrastructure will not affect the flood peaks in the rivers.

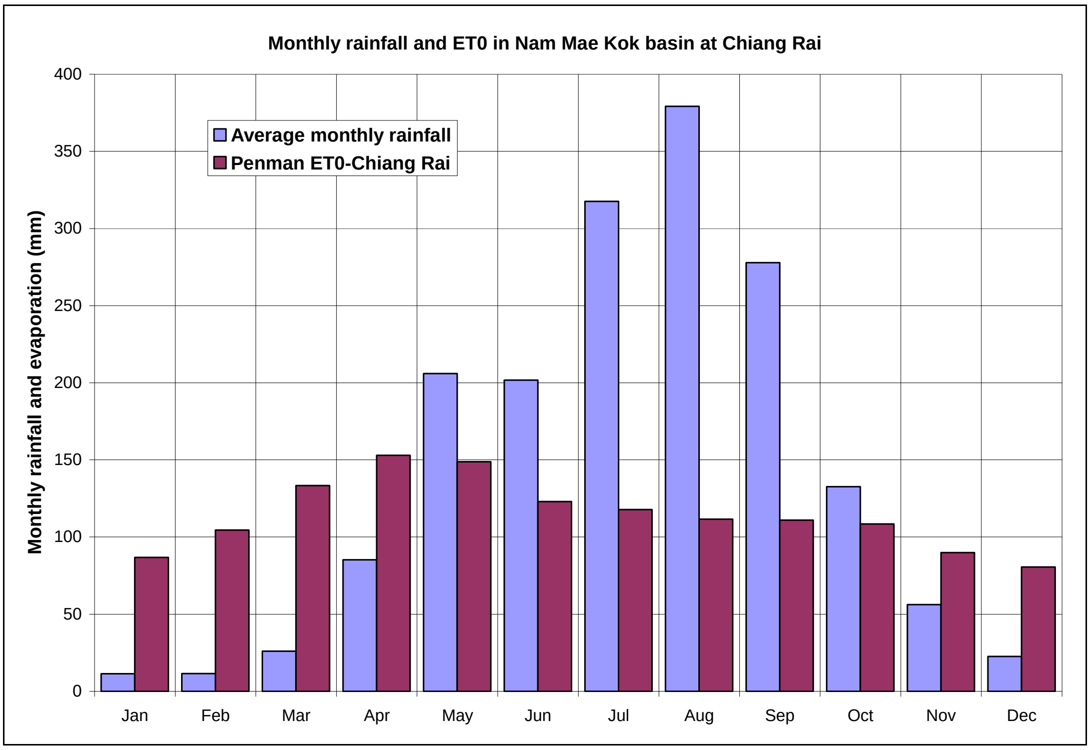

Figure 3-15 Average monthly rainfall and reference evaporation at Chiang Rai.

3.6.3 Water levels and stage-discharge relations

Water levels are available in the MRC database for 6 gauging stations in the Nam Mae Kok and tributaries, with records from at the earliest 1969 until the latest in 2005. Additional water level data were received to complete the MRC-series up to 2007. The water level series for Ban Pong Na Kham, Ban Mae Phaeng, and Ban Pong Pu Fuang were added to the MRC database.

Since the construction of the weir in the early nineties station Chiang Rai is some 5 km downstream of the measuring location, affected by backwater. Station Ban Tha Sai on Nam Mae Lao is outside the backwater reach of the Nam Mae Kok; the station is at 15.8 km from the mouth and with a river slope of 5.8×10^{-4} and an equilibrium depth of 4 m the backwater from the Kok River reaches only to about 7 km from the mouth. However, the Chai Sombat Weir on the Nam Mae Lao is located only 3 km downstream of the station, and affects the readings at Ban Tha Sai.

Stages on the Nam Mae Kok and tributaries appear to vary widely for a particular discharge. These variations are found in the stage-discharge relations of basically all stations. A few examples:

- At Chiang Rai the variation in water level for a discharge of 350 m^3/s for the period 1977-1986 is 0.40 m, and for the period 1987-1992 is 0.80 m, whereas for lower discharges the variation is even larger.

- At Ban Tha Ton no gauge change is mentioned in the yearbooks, but the variation in the water level for a discharge of 100 m^3/s is seen to be about 0.75 m, see Figure 3-16. The water level record shows a shift of 1 m on 1/1/2005.
- At Ban Tha Mai Liam, no gauge change is mentioned in the yearbooks, but the variation in the water level for a discharge of 100 m^3/s in the available period amounts to 2.20 m.
- At Ban Tha Sai no change is mentioned in the yearbooks, but the variation in the water level for e.g. a discharge of 100 m^3/s is about 0.90 m.

Though these variations suggest that no registered changes in the gauge setting may have taken place, from an inspection of the available stage-discharge data it is revealed that sufficient data is available to establish each year a new rating curve. Apparently, the changes can, with a few exceptions, be attributed to large morphological changes. The large variations from one year to another in the discharge ratings create therefore an additional uncertainty in the computed water levels and should be taken into account as an additional stochastic variable. Its effect can be introduced by adjustment of the hydraulic roughness.

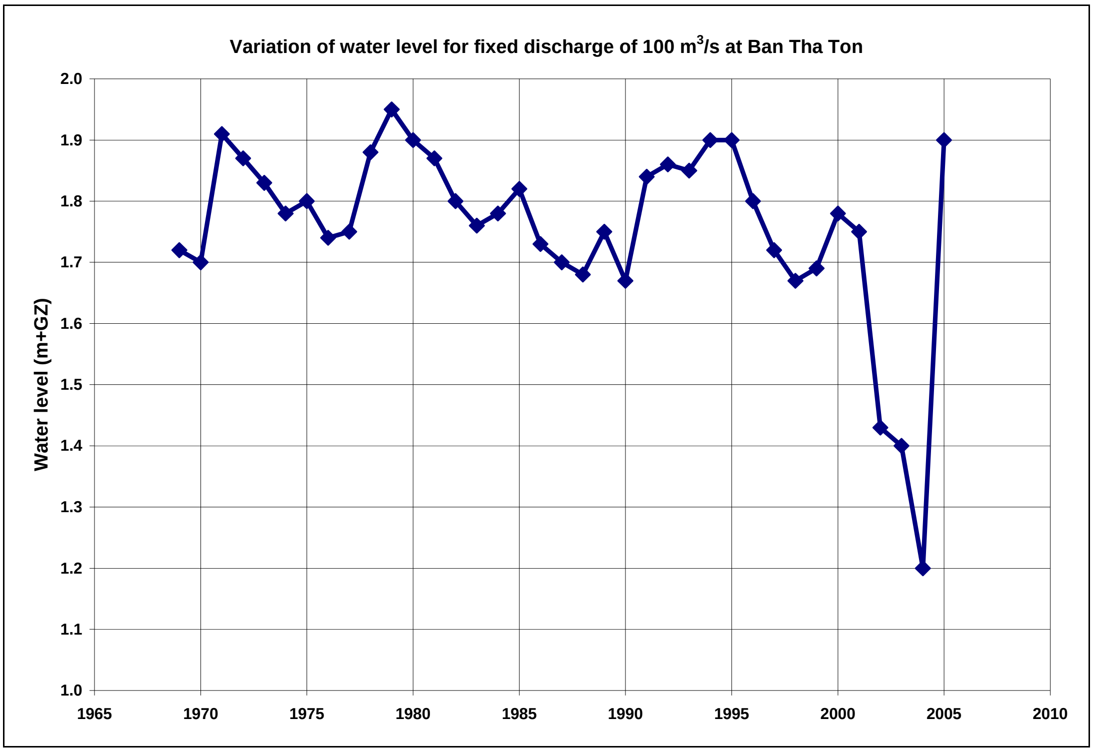

Figure 3-16 Variation in gauge reading for fixed discharge of 100 m3/s in the Nam Mae Kok at Ban Tha Ton.

In the frame of the project “Strengthening of Flood Management Capacity for the Kok River in Chiang Rai Province” financed by MRC, which started in 2007, automatic stations at the a number of locations have been implemented. These may in future provide important data for calibration and verification of the hydraulic model. However for statistical analysis their series are too short.

3.6.4 Discharges

To validate the discharge series, double mass analysis has been carried out on the series. Since the rainfall records in the Nam Mae Kok Basin showed straight lines on double mass plots, a similar behaviour is expected for the discharge series. In the double mass analysis the series of

Ban Tha Ton and Chiang Rai did not show anomalies. However, the series of Ban Tha Mai Liam on Fang compared to Ban Tha Ton shows a break in 1995. Also, the discharge series of Ban Tha Sai on Lao shows a break in 1981 compared to Ban Tha Ton as well as to Ban Tha Mai Liam. One reason may be changing water abstractions as on tributaries of both Fang and Lao rivers reservoirs have been constructed. The series of Ban Pong Pu Fuang did show to be consistent with the series of Ban Tha Sai. Anomalies were encountered for Ban Pong Na Kham and Ban Mae Phaeng:

- In the series of Ban Pong Na Kham inconsistencies were found for the period 1988-1994, which period coincides with the non-availability of water level data. Apparently, data for this period had been completed by rainfall-runoff modelling.
- The series of Ban Mai Phaeng appears to be entirely inconsistent with the area adjusted sum of the flows at Ban Pong Na Kham and Ban Pong Pu Fuang. Only for a few years a reasonable match was found. Generally the series is much too high and its peak values are unrealistically large. Since this series was used by Kittipong (2009, page 49) in a water balance analysis to calibrate the lateral inflows from SWAT, it follows that these lateral inflows will be too high as well.

Monthly and annual flow statistics of the Nam Mae Kok at station Chiang Rai (u/s Lao confluence) and Nam Mae Lao at Ban Tha Sai are presented in Table 3-8. Note that the flow series of Chiang Rai has been extended based on records of Ban Tha Ton and Ban Tha Mai Liam, see next chapter. Graphics of the annual flows and of the monthly statistics are shown in Figure 3-17, Figure 3-19 and Figure 3-20. The annual flows show a downward trend in Chiang Rai as well as in Ban Tha Sai. This trend is apparently the result of higher rainfall in the seventies as may be observed from the annual runoff/rainfall ratio, which does not show any trend for the same period (see Figure 3-18).

Table 3-8 Monthly and annual flow statistics (in MCM and mm) of the Nam Mae Kok at Chiang Rai and Nam Mae Lao at Ban Tha Sai.

Chiang Rai	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Mean (MCM)	160.5	102.2	85.0	73.9	129.1	186.8	399.9	718.5	715.4	489.1	333.7	223.0	3617.2
Stdv (MCM)	32.2	20.4	18.7	18.2	60.4	58.9	151.1	249.6	182.2	118.5	93.2	58.2	725.1
Depth (mm)	26.5	16.9	14.0	12.2	21.3	30.8	66.0	118.6	118.1	80.7	55.1	36.8	596.9
Stdev (mm)	5.3	3.4	3.1	3.0	10.0	9.7	24.9	41.2	30.1	19.6	15.4	9.6	119.7
Ban Tha Sai													
Mean (MCM)	25.6	11.4	8.0	9.7	36.9	45.4	73.4	159.1	201.3	131.8	93.7	49.4	845.7
Stdv (MCM)	16.5	7.3	5.7	6.8	29.3	28.3	52.7	80.2	74.9	42.9	43.2	19.2	257.9
Depth (mm)	8.3	3.7	2.6	3.2	12.0	14.7	23.8	51.6	65.4	42.8	30.4	16.0	274.6
Stdev (mm)	5.4	2.4	1.8	2.2	9.5	9.2	17.1	26.0	24.3	13.9	14.0	6.2	83.7

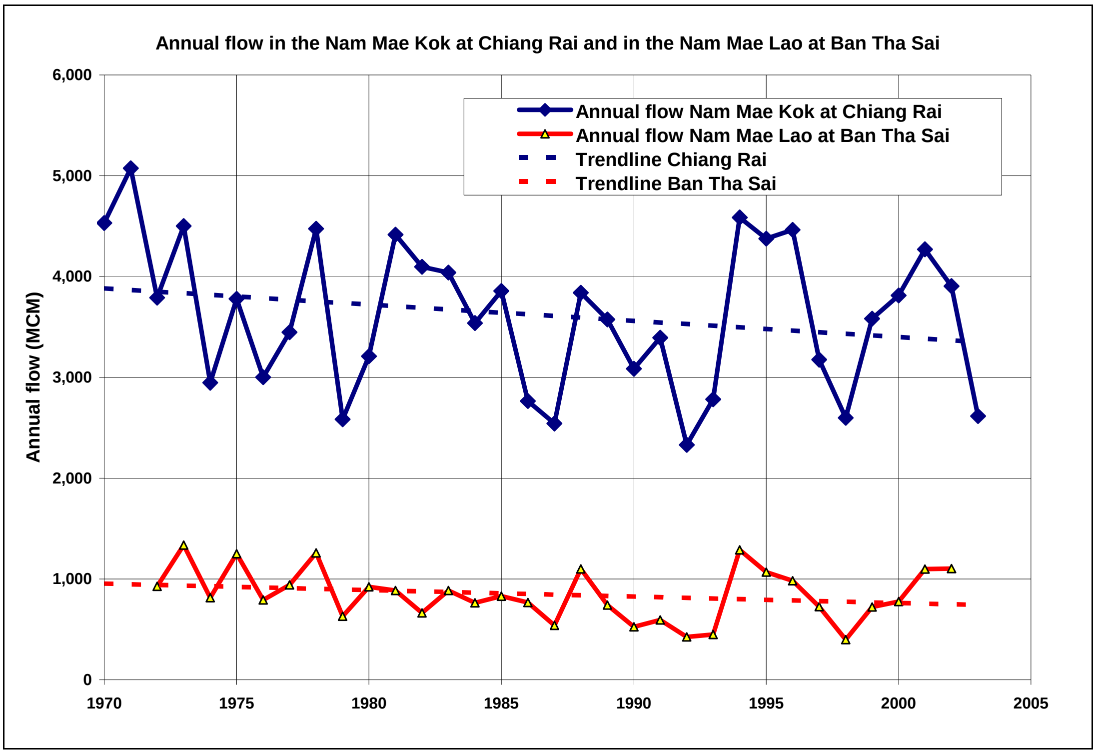

Figure 3-17 Annual runoff in the Nam Mae Kok at Chiang Rai and Nam Mae Lao at Ban Tha Sai.

Monthly flows in the Nam Mae Kok at station Chiang Rai are largest in August-September, whereas in the Nam Mae Lao at Ban Tha Sai the maximum flow generally occurs in September. As can be observed from Figure 3-21 the runoff-depth from the Nam Mae Kok at Chiang Rai is larger than of the Nam Mae Lao at Ban Tha Sai. Note that at both locations the flow regime is affected by reservoirs upstream: on Nam Mae Kok at Chiang Rai by reservoirs on tributaries of the Nam Mae Fang and on Nam Mae Lao by tributaries upstream of Ban Tha Sai). Discharge frequency curves of Nam Mae Kok (downstream of Lao confluence) and Mekong at Chiang Saen are shown in Figure 3-22 and Figure 3-23 with a comparison in Figure 3-24. Special attention is drawn to the latter, which shows that the Mekong peaks slightly ahead of the Nam Mae Kok. This is elaborated further in the next chapter, dealing with the hydrological hazard.

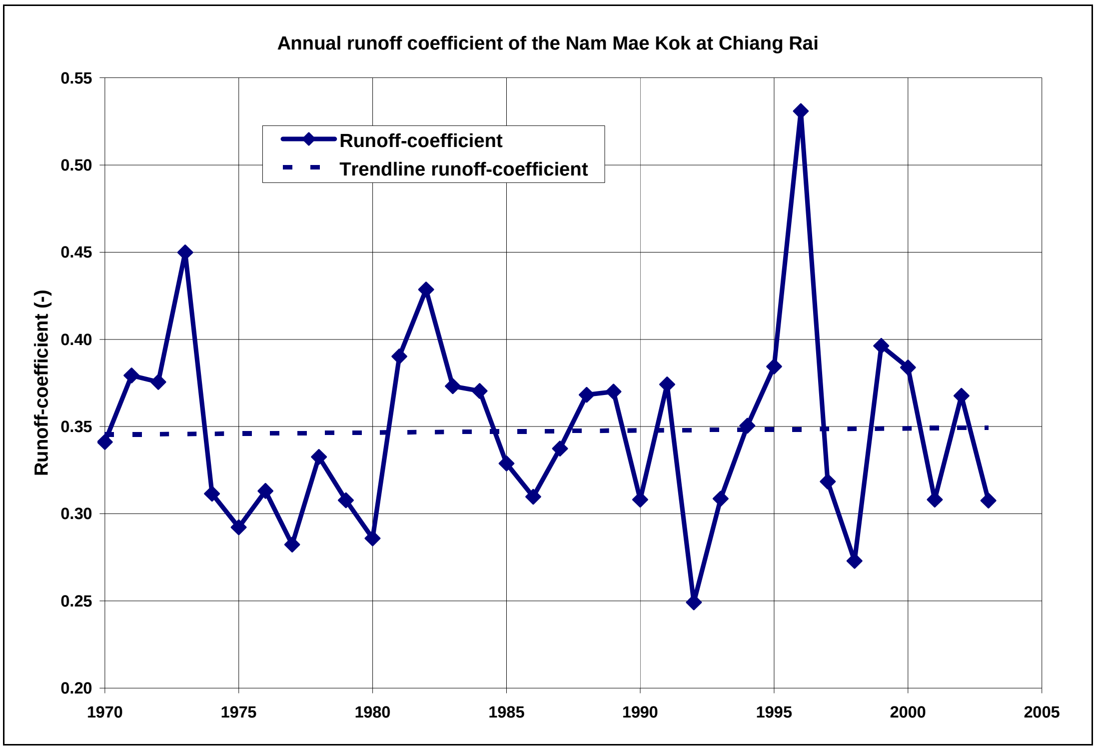

Figure 3-18 Runoff-coefficient of the Nam Mae Kok at Chiang Rai.

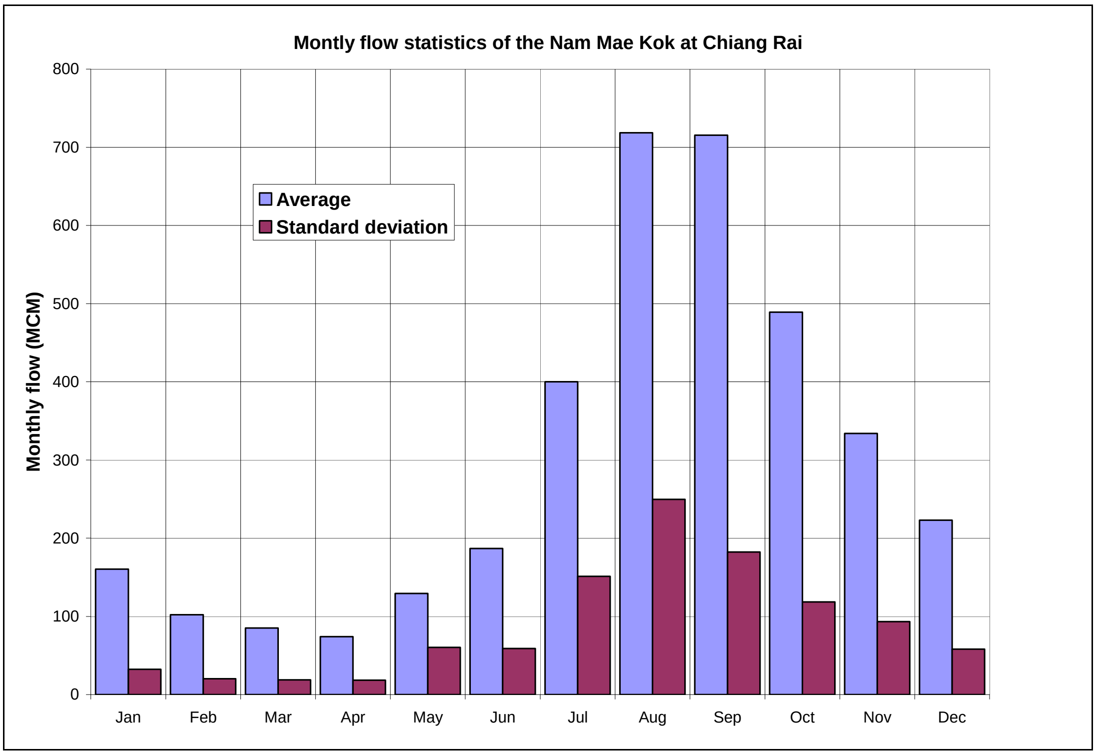

Figure 3-19 Monthly flow statistics of the Nam Mae Kok at Chiang Rai.

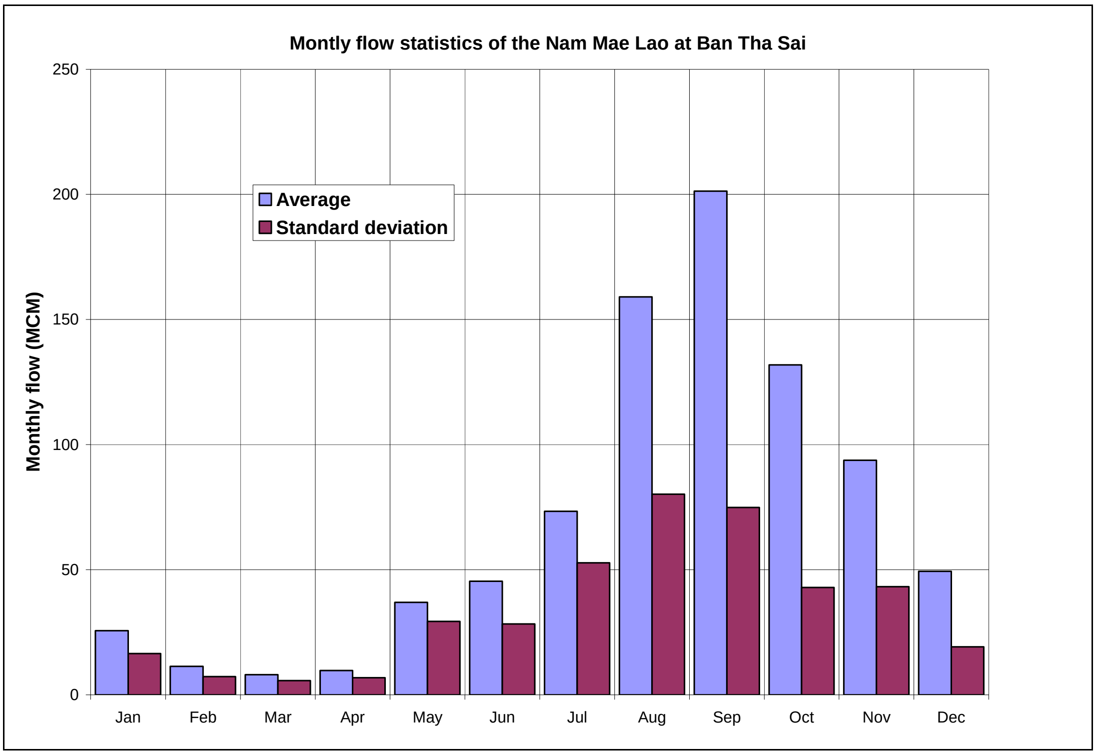

Figure 3-20 Monthly flow statistics of the Nam Mae Lao at Ban Tha Sai.

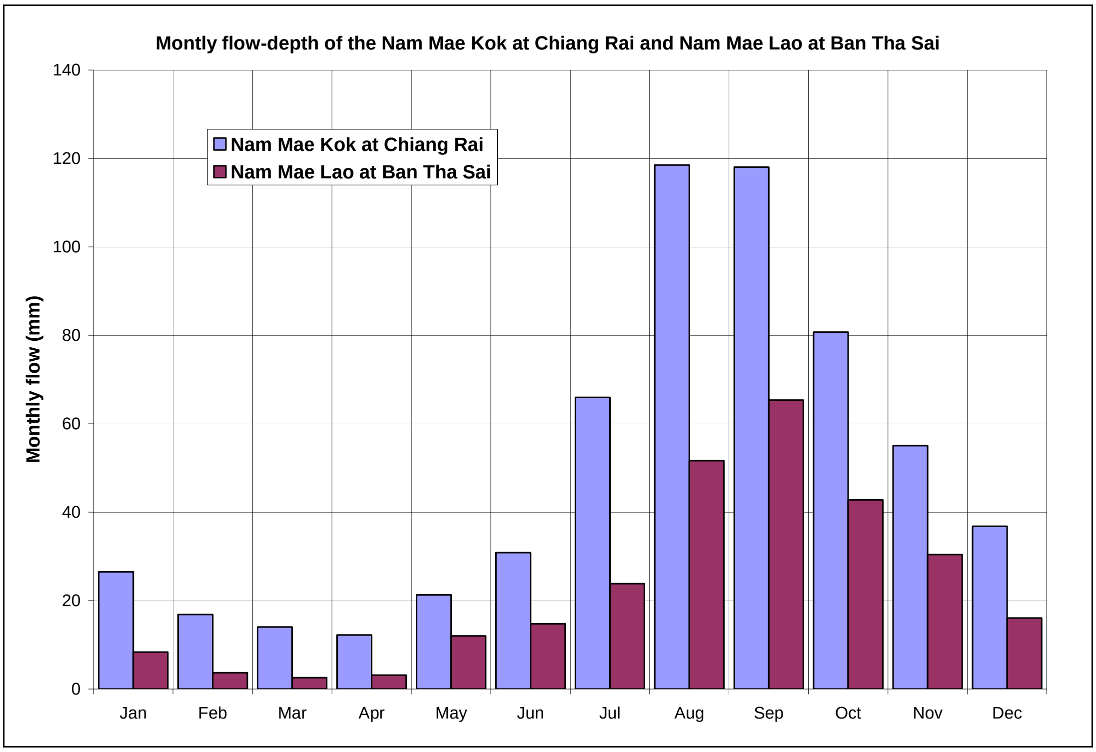

Figure 3-21 Comparison of monthly flow depth in Kok at Chiang Rai and Lao at Ban Tha Sai.

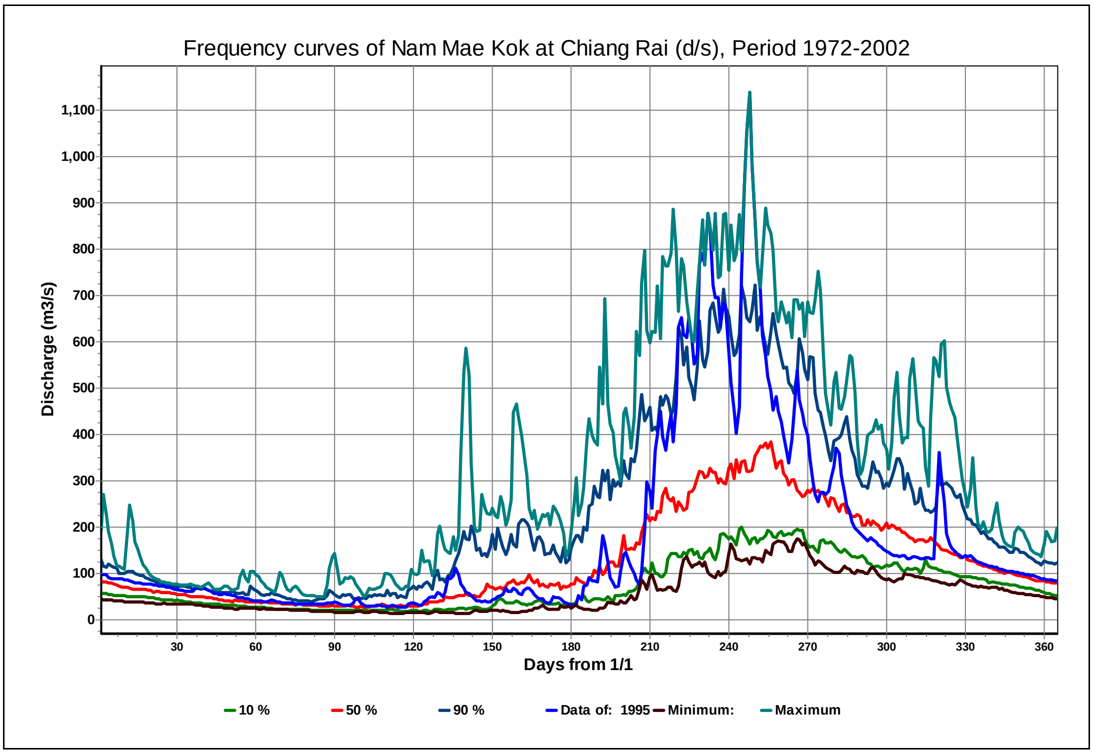

Figure 3-22 Discharge frequency curves Nam Mae Kok d/s Nam Mae Lao, period 1972-2002.

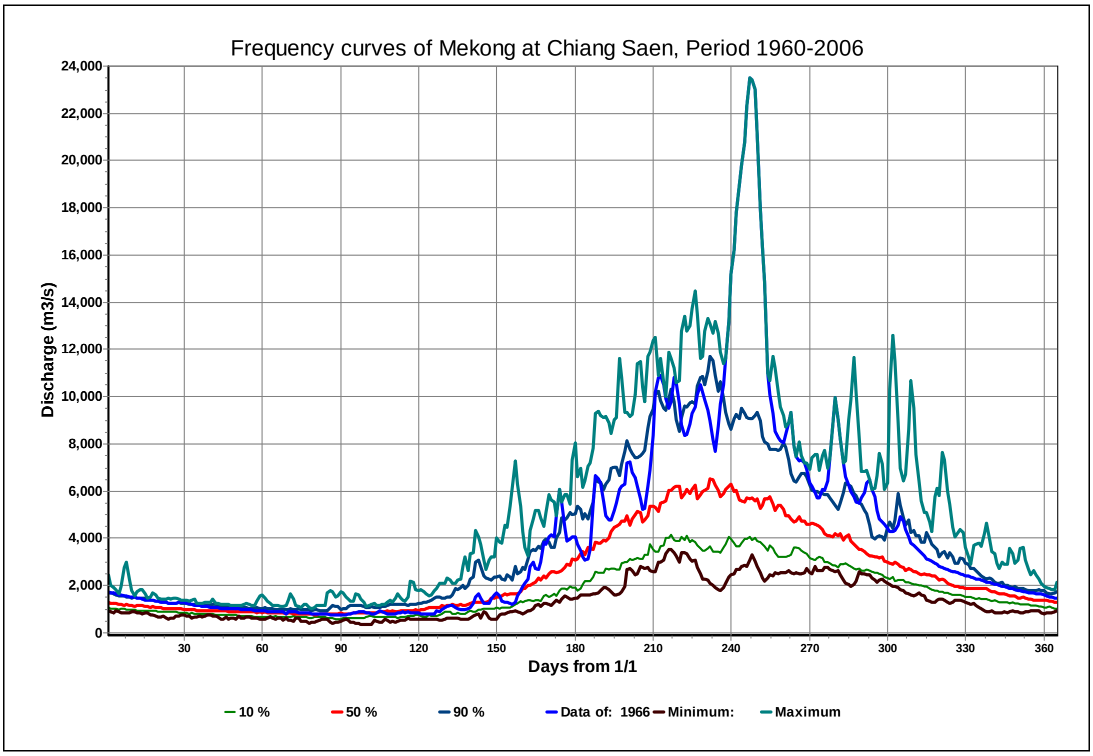

Figure 3-23 Discharge frequency curves Mekong at Chiang Saen, period 1960-2006.

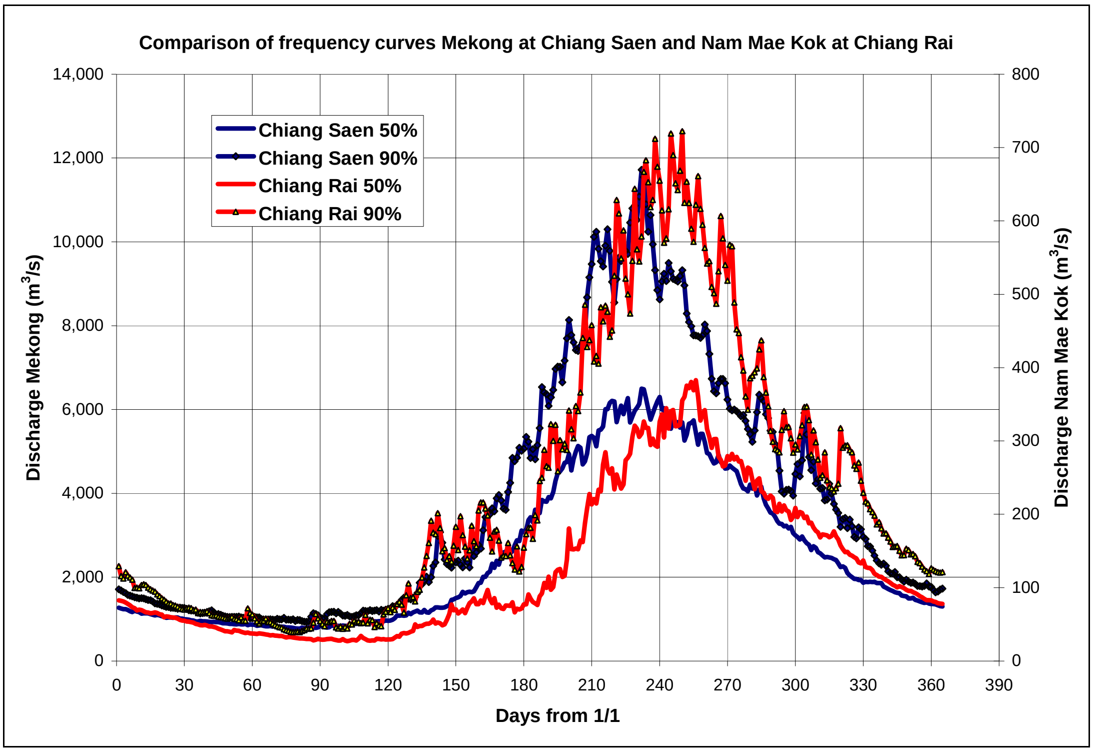

Figure 3-24 Comparison of discharge frequency curves of Mekong at Chiang Saen and Nam Mae Kok d/s of Chiang Rai.

CHAPTER 4

HYDROLOGICAL HAZARD

4 HYDROLOGICAL HAZARD

4.1 General

The flood hazard in the Nam Mae Kok is derived from the hydrological hazard, i.e. flow probabilities transformed into water levels and flow velocities for selected return periods using a hydraulic model of the river and floodplain. The area of concern is the Chiang Rai region along the Nam Mae Kok and Nam Mae Lao/ and the Nam Mae Kok downstream of Chiang Rai up to its confluence with the Mekong. To arrive at the flood hazards the following procedure is advocated:

1. For flood hazard assessment along the Nam Mae Kok in the Chiang Rai region **upstream** of the Lao confluence the analysis can be based on the statistics of the flow in the Nam Mae Kok at station Ban Pong Na Kham. Lateral inflow upstream Chiang Rai Weir is from the Nam Mae Korn. The downstream condition is formed by the Chiang Rai Weir formula.
2. For flood hazard assessment along the Nam Mae Kok in the Chiang Rai region **downstream** of the Lao confluence the analysis can be based on the statistics of the total flow in the Nam Mae Kok and Nam Mae Lao at Ban Pong Na Kham and Ban Pong Pu Fuang, corrected for lateral inflow based on drainage areas. For lateral inflow a fraction of the Kok flow at the Lao confluence is taken. The downstream boundary condition is a discharge rating at Sop Kok in the Mekong with an average Mekong hydrograph at Chiang Saen.
3. For flood hazard assessment along the Lower Nam Mae Lao the analysis can be based on the statistics of the flow in the Nam Mae Lao at station Ban Pong Pu Fuang, with for the Nam Mae Kok the flow passing station Chiang Rai at the time of the occurrence of the annual peaks at Ban Pong Pu Fuang, with a similar procedure for the lateral inflow further downstream. The Nam Mae Korn contribution is a derived from Ban Pong Pu Fuang, see under 5.
4. For flood hazard assessment along the Lower Nam Mae Kok near to the mouth of the river the combined occurrence of the Nam Mae Kok flow d/s Chiang Rai (Nam Mae Kok and Nam Mae Lao with area correction) and the discharge rating in the Mekong at Sop Kok is considered.
5. The flow in the Nam Mae Korn is proposed to be derived from the flow in the Nam Mae Lao proportional to the areas and corrected for runoff percentages as observed from 2000-2005.

The base of the flood hazard, the hydrological hazard, is elaborated in this chapter.

4.2 Nam Mae Kok at Ban Pong Na Kham

Peak discharge

The flow extremes in the Nam Mae Kok upstream of Chiang Rai at Ban Pong Na Kham have been derived from the annual maximum daily discharge in the period 1967-2007 (see Figure 4-2) as follows:

1. For the periods 1967-1987 and 1995-2007 use has been made of the discharge record of Ban Pong Na Kham.
2. In the original record the data for the period 1988-1994 is missing. The series for this period used by Kittipong (2009) for flood mapping appeared to be inconsistent with the

observations at Chiang Rai and the sum of Ban Tha Ton and Ban Tha Mai Liam. Since the series of Chiang Rai and the sum of Ban Tha Ton and Ban Tha Mai Liam are mutually consistent the former has been used to replace Ban Pong Na Kham for the period 1/1/1988-30/11/1993. For the period 1/12/1993-31/12/1994 in view of backwater of the Chiang Rai Weir on station Chiang Rai the flow at Ban Pong Na Kham has been estimated from 1.2 x (Ban Tha Ton + Ban Tha Mai Liam). The resulting original and adjusted annual maximum series are shown below.

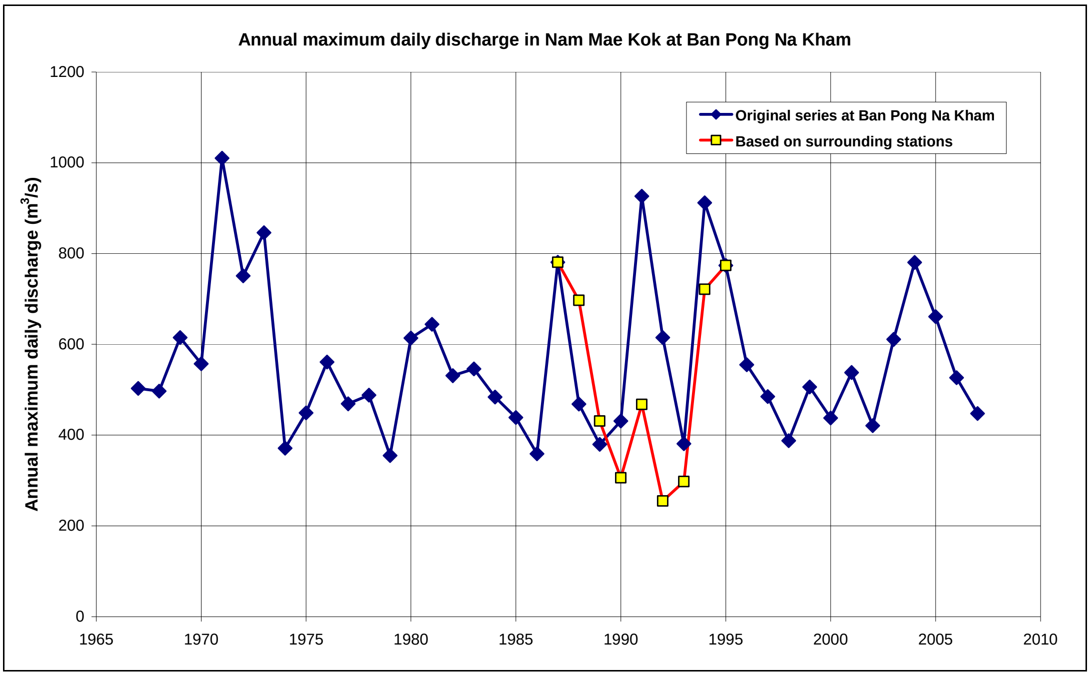

Figure 4-1 Annual maximum daily discharge in Nam Mae Kok at Ban Pong Na Kham, with adjustment based on surrounding stations.

Note that the series of annual extreme discharges may not entirely be natural as in the Nam Mae Fang a small part of the discharge is controlled by reservoirs. In-homogeneities in the discharge series caused by reservoir operation are ignored in the following analysis.

EV1 (= Extreme Value Type 1 or Gumbel) and GEV (= General Extreme Value) distributions have been used to fit the observed distribution of annual extreme discharges at Chiang Rai. The distributions have the following form:

$$EV1: \quad F(x) = \exp\left\{-\exp\left[-\left(\frac{x-u}{\alpha}\right)\right]\right\}$$

$$GEV: \quad F(x) = \exp\left\{-\left(1-k\left(\frac{x-u}{\alpha}\right)\right)^{1/k}\right\} \tag{4.1}$$

where: F(x) = distribution function

k, α, u = shape, scale and location parameters of the distribution

The result, using probability weighted moments (see Cunnane, 1989), is presented in Table 4-1 and Figure 4-2. Tests indicate that the hypothesis of k = 0 (i.e EV1 distribution) is not rejected at a 5% significance level. It may be observed that both distributions give similar values for the discharges at selected return periods.

It is noted that the tabulated discharges refer to daily average flows. The hazard assessment requires instantaneous maxima. Based on comparison of instantaneous maximum values with daily average values for Ban Pong Na Kham it appears that a correction factor on average of 1.044 is to be applied to the daily average maxima, as shown in Figure 4-3.

Table 4-1 EV1 and GEV-parameters of peak-discharge and values for distinct return periods in the Nam Mae Kok and Nam Mae Lao around Chiang Rai.

Parameter	Nam Mae Kok Ban Pong Na Kham	Nam Mae Lao Ban Pong Pu Fuang	Nam Mae Kok Chiang Rai d/s Lao confluence
years	1967-2007	1971-2007	1971-2007
EV1			
α	131.8	67.2	205.5
u	464.8	153.2	635.3
T (years)			
2	513	178	711
5	663	254	944
10	762	304	1098
25	887	368	1293
50	979	415	1437
100	1071	462	1580
GEV			
k	0.034	-0.160	0.065
α	136.0	56.7	217.4
u	466.9	149.1	641.6
T (years)			
2	516	171	720
5	666	245	952
10	761	303	1097
25	879	386	1270
50	963	456	1391
100	1046	534	1506

To transform the discharge extremes into water level extremes no use can be made of a discharge rating curve as the water levels in the Nam Mae Kok at Chiang Rai are also controlled by the Chiang Rai Weir downstream of the city. Use of a hydraulic model is unavoidable for this location. The annual maximum peaks on the Nam Mae Kok at Ban Pong Na Kham occurred with only a few exceptions in the months August and September, with 1 September as the median occurrence date. There is no relation between peak size and date of occurrence.

Flood volume and flood shape

Beside maximum water levels also flood duration is also of importance to flood volume and flood hydrographs of the Nam Mae Kok at Chiang Rai have been investigated. The relation between flood volume and peak flow has been derived from the annual maximum flow at Ban Pong Na Kham and the flood volume from 15 days before till 15 days after the occurrence of the peak. The relation is shown in Figure 4-4; it has a standard error of 129 MCM.

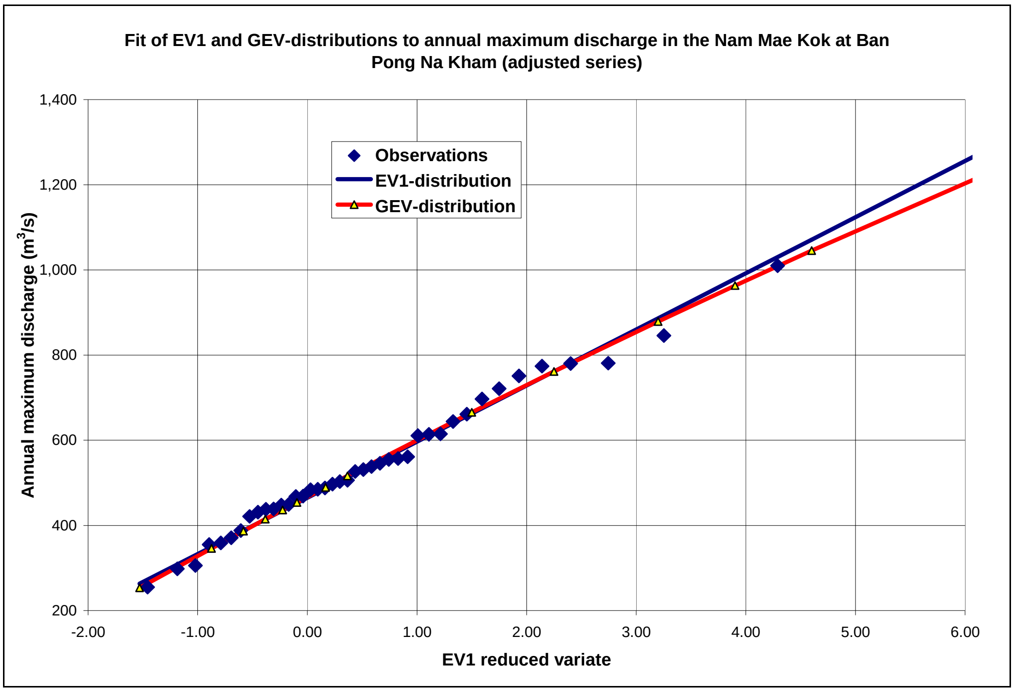

Figure 4-2 Fit of EV1 and GEV-distributions to annual maximum discharge in Nam Mae Kok at Ban Pong Na Kham (adjusted series), period 1967-2007.

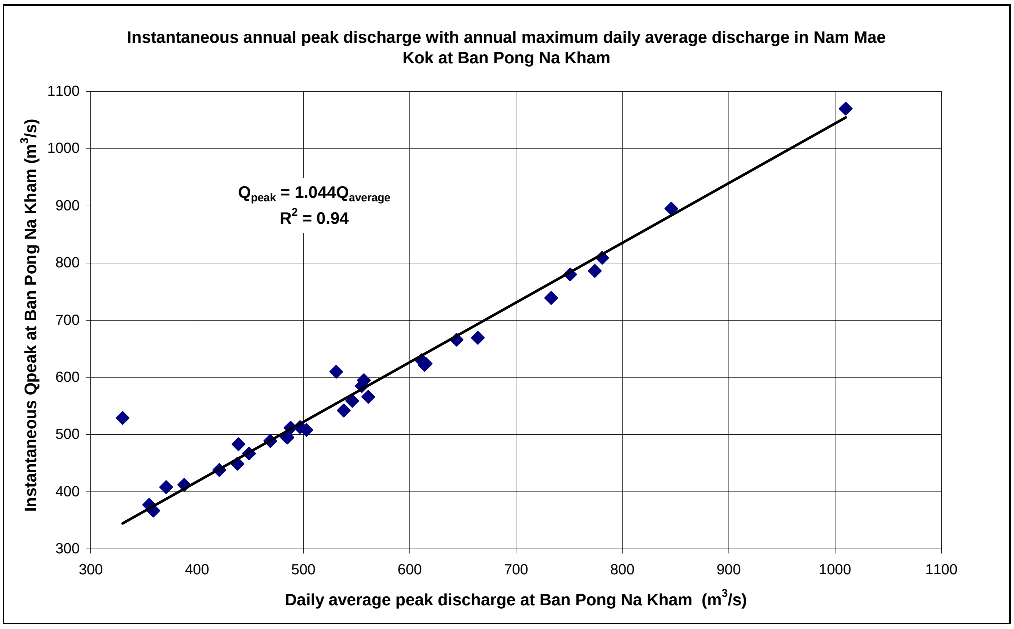

Figure 4-3 Comparison of instantaneous peak discharge and annual maximum daily average discharge in Nam Mae Kok at Ban Pong Na Kham, periods 1967-1987, 1995-2005.

For defining the hydrograph shape the 20 largest flood peaks since 1966 at Ban Pong Na Kham have been selected, and their shapes from 15 days prior to 15 days after the occurrence of the peak were considered. Each hydrograph has been made dimensionless by dividing the ordinates by their peak value ($Q/Q_{max}(t)$ for t = -15,..,15). Next, for each time t the $Q/Q_{max}(t)$-values were ranked in ascending order and equal ranked values of different times have been combined to arrive at dimensionless hydrographs for 5%, 10%,…,90%, 95% non-exceedance probabilities. Examples of lean, medium and wide hydrographs are shown in Figure 4-5. It is observed that for a median flood wave typically 50% of the peak value is exceeded from 6 days prior to the peak to 6 days after the peak. Hence, the flashiness of tributary floods as observed in the uplands does not exist anymore in the Nam Mae Kok at Chiang Rai.

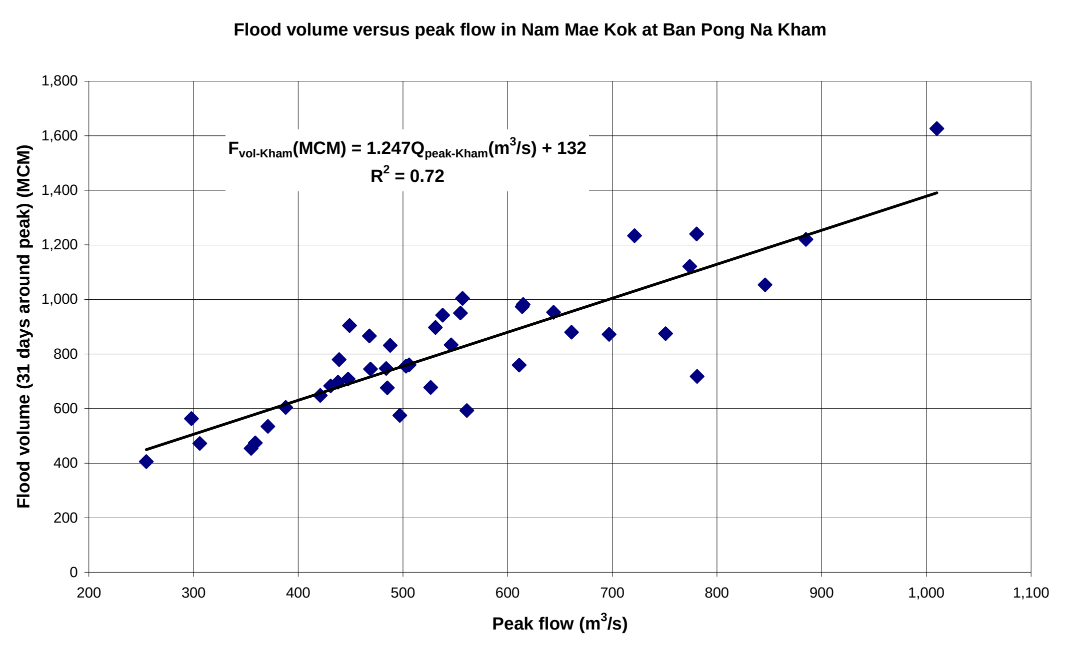

Figure 4-4 Flood volume in Nam Mae Kok at Ban Pong Na Kham as function of daily average peak flow.

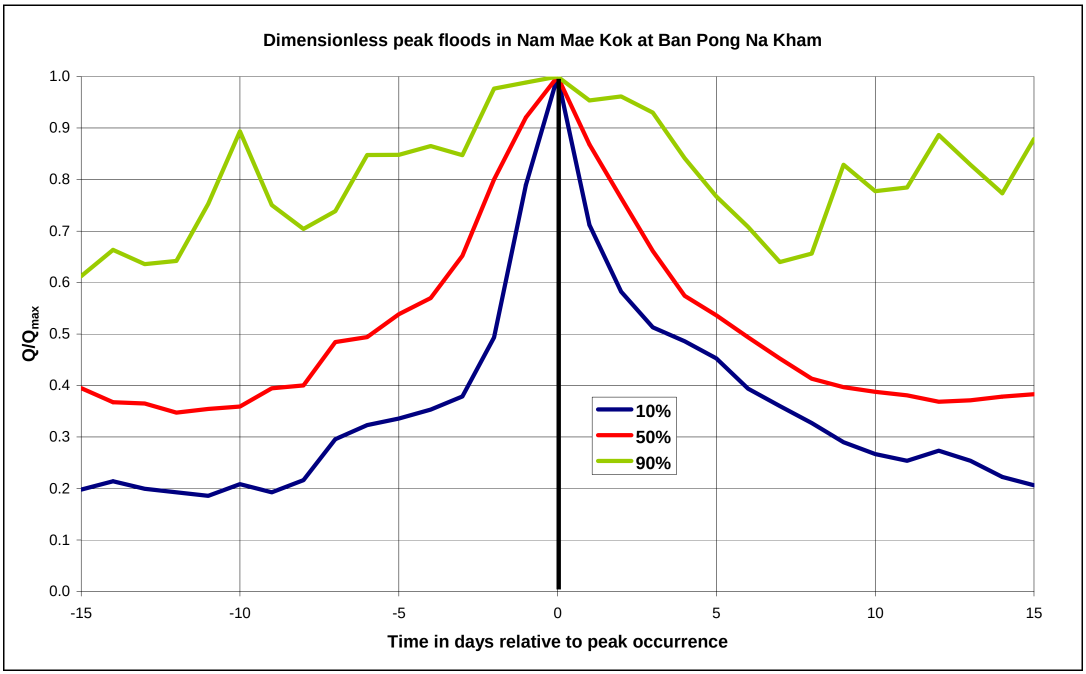

Figure 4-5 Example of dimensionless hydrographs in Nam Mae Kok at Ban Pong Na Kham.

Lateral inflow

Downstream of Ban Pong Na Kham, up to the Chiang Rai Weir, the flow in the Nam Mae Kok is augmented with discharge from the Nam Mae Korn. Actual flow records for the Korn are only available for station Ban Pang Rim Korn G4 for the period 4/2000-3/2007. Kittipong (2009) derived lateral inflow to the Korn from rainfall-runoff modelling. The derived inflow appears to be extremely high in comparison to the flow at station G4. At the upstream boundary of the hydraulic model of the Korn the basin area is 114.2 km^2. The inflow is taken as 2.3 x G4 and is shown for 2006 in Figure 4-6. The total basin area of the Korn is 162 km^2. So the lateral inflow represents the runoff of an urban area of 47.8 km^2, i.e less than half of the basin at the model boundary. The lateral inflow for 2006 is also shown in Figure 4-6. The lateral inflow volume from 2000 to 2006 is 2.3 times larger than the upstream inflow (i.e. a 5.5 times higher runoff coefficient), whereas the lateral peak-inflow values are often 4 times larger than the upstream inflow peaks. Also the lateral inflow signal deviates substantially from the recorded upstream inflow. Higher runoff rates per unit area and peak flows are expected in view of the urban terrain but these differences appear to be too large. The lateral inflow as applied by Kittipong (2009) has been based on a water balance between the upstream hydraulic model boundaries and the record of the Nam Mae Kok at Ban Mae Phaeng. But as explained in Section 4.4, the latter series overestimates the actual discharge largely, leading to 2.3 times larger lateral inflow estimates. This scales the lateral inflow volume down to about the same volume as the upstream inflow volume. The SWAT generated lateral inflow series, however, has shown to be inconsistent with the Lao discharge at Ban Pong Pu Fuang and its peakedness deviates substantially from the G4-series. In view of this the SWAT-series is completely discarded and the following procedure is proposed for the modelling of the Korn solely:

- The upstream boundary of the Korn is derived from the Ban Pong Pu Fuang series multiplied by a factor 0.16; this series can be shown to provide similar extremes as the original G4 record.
- The lateral inflow to the Korn is taken equal to 0.42 times the upstream inflow accounting for area differences (47.8 versus 114.2 km^2); it is assumed that reduced slope further downstream compensates for larger urbanisation (= 0.07 times the flow at Ban Pong Pu Fuang).

So, the total outflow from the Korn into the Kok upstream of Chiang Rai Weir is 0.22 times the flow at Ban Pong Pu Fuang, whereas based solely on area, a factor of 0.06 would have been found. Hence, the runoff percentage of the Korn would be almost 4 times larger than the Lao at Ban Pong Pu Fuang and nearly 2 times larger than of the Kok upstream Chiang Rai. A further investigation into the validity of the G4 record would be required.

For flood hazard assessment along the Kok u/s Chiang Rai Weir the model boundary and lateral inflow has to be obtained from Lao hydrographs (see next section) as follows:

- The discharge in Nam Mae Lao during passage of peak in the Nam Mae Kok is on average 185 m^3/s with a standard deviation of 75 m^3/s
- The flow volume of the Nam Mae Lao during the passage of the flood in the Nam Mae Kok can be derived from:

$$F_{vol,Fuang} = 0.17\ F_{vol,Kham} + 81 \quad (MCM) \qquad Se = 70\ MCM \tag{4.1}$$

where: $F_{vol,\ Fuang}$ = flow volume in Lao at Ban Pong Pu Fuang
$F_{vol,\ Kham}$ = flow volume in Kok at ban Pong Na Kham
Se = standard error about regression

To the above values a multiplier of 0.16 and 0.07 has to be applied for the upstream and lateral inflow respectively.

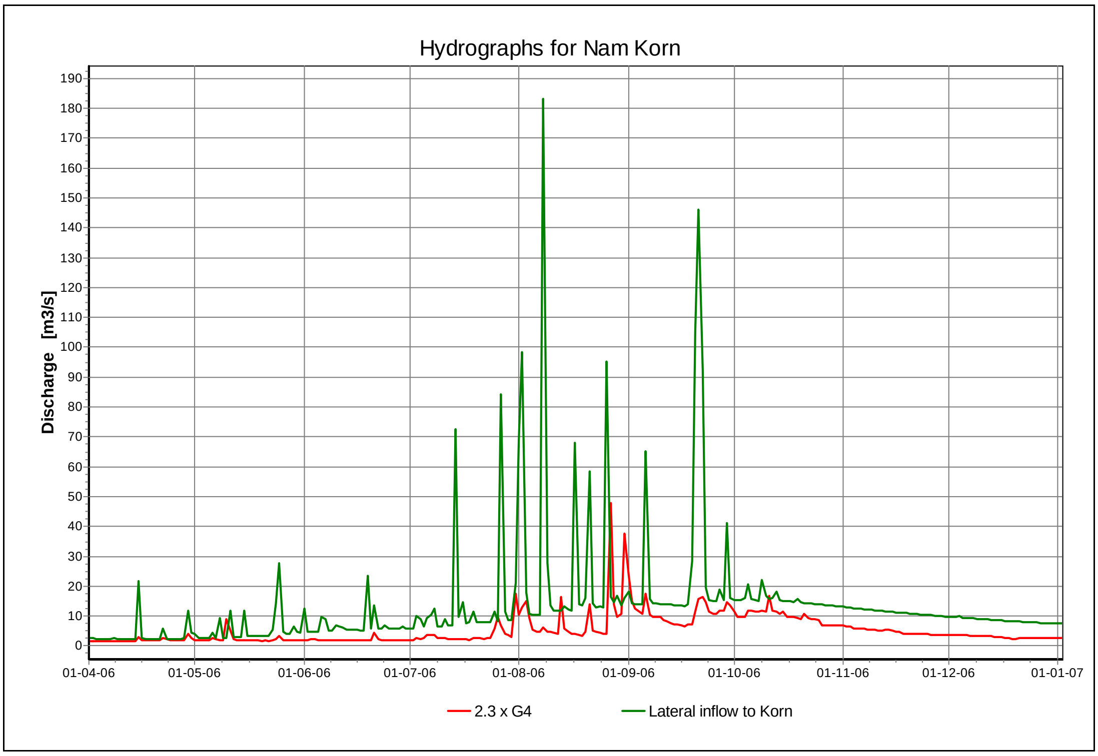

Figure 4-6 Upstream and lateral inflow to hydraulic model of Nam Mae Korn, year 2006.

Downstream boundary

For flood mapping along the Nam Mae Kok in Chiang Rai, the hydraulic model results up to Chiang Rai Weir are to be used. During extreme floods it is assumed that the gates of the weir will be fully opened. Hence, the weir relation can be applied as a downstream boundary.

Morphology

The water levels at Ban Pong Na Kham for a discharge of 450 m^3/s have varied historically at about 0.80 m. Relative to the model calibration period the levels for this discharge has been 0.20 m higher to 0.60 m lower. This effect is to be included by adjusting the calibrated Manning n.

4.3 Nam Mae Lao at Ban Pong Pu Fuang

Peak discharge

The annual maximum discharges in the Nam Mae Lao at Ban Pong Pu Fuang have been abstracted from the available discharge series for this station covering the period 1971-2007. The floods peaks are compared with those observed at Ban Tha Sai, further downstream on Nam Mae Lao in Figure 4-7. It is observed that the annual maxima of Ban Pong Pu Fuang are much more pronounced than those at Ban Tha Sai, though the basin area at the latter is about 19% larger (2,585 against 3,080 km^2). Inspection of the water level record at the two stations for selected years gives the impression that during peak flows the gauge at Ban Tha Sai has been overtopped a few time, as a constant water level is occasionally observed during the passage of the peaks, see Figure 4-8. However, based on the information gathered during the field visit, overtopping of the embankment between the two sites, limiting the peak flow at Ban Tha Sai in the past (at least prior to 2005), has very likely been the cause of the smooth record. Recent records show more variation at Ban Tha Sai, see Figure 4-9.

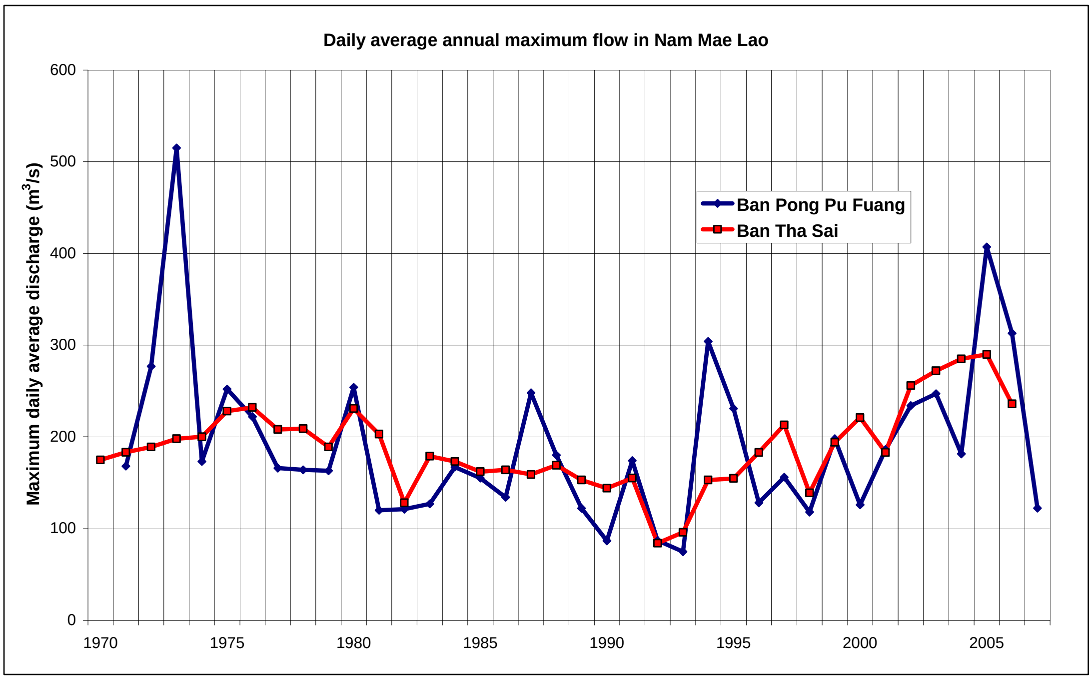

Figure 4-7 Annual maximum discharge in Nam Mae Lao at Ban Pong Pu Fuang and Ban Tha Sai.

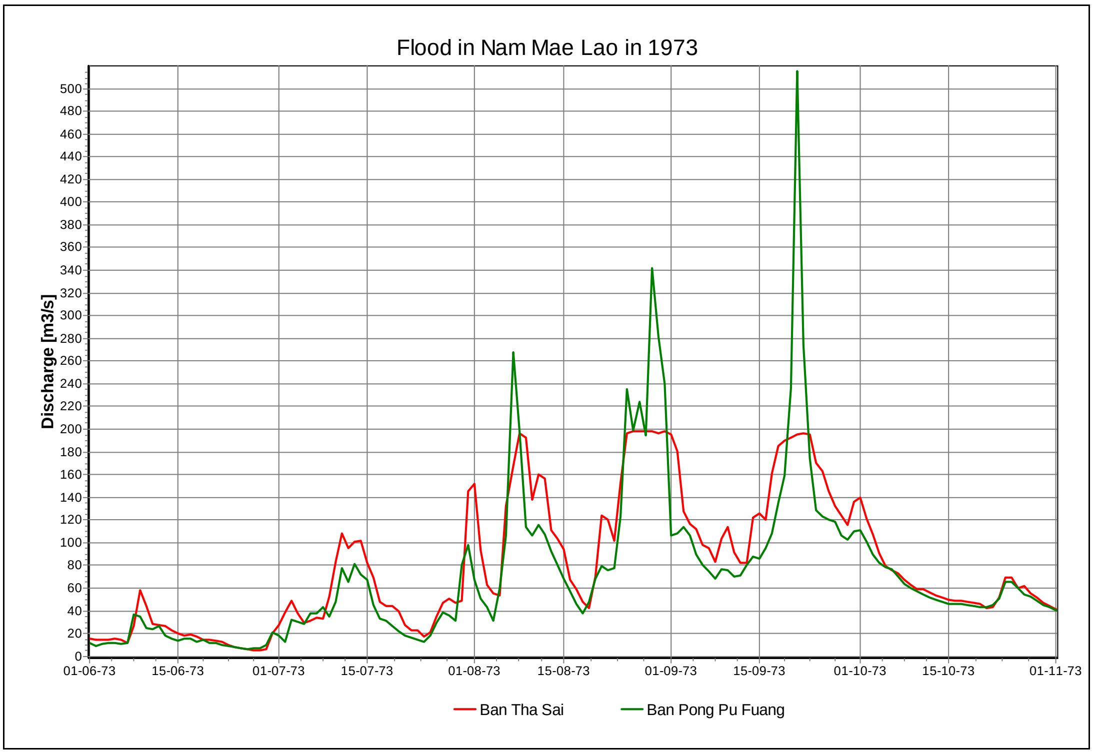

Figure 4-8 Flood hydrographs of Nam Mae Lao at Ban Pong Pu Fuang and Ban Tha Sai, year 1973.

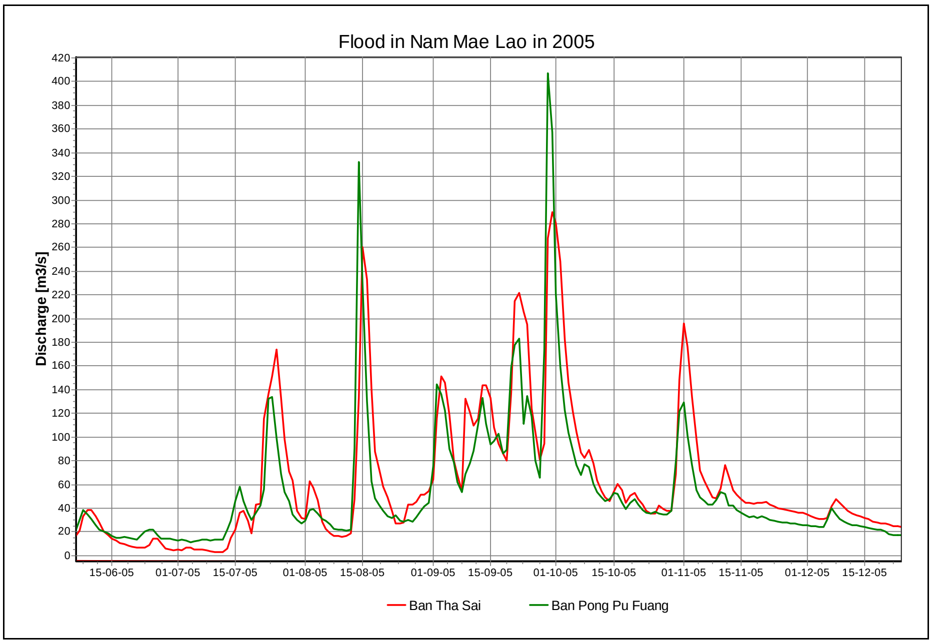

Figure 4-9 Flood hydrographs of Nam Mae Lao at Ban Pong Pu Fuang and Ban Tha Sai, year 2005.

It follows that for flood hazard assessment along the Lao the record of Ban Pong Pu Fuang, rather than of Ban Tha Sai has to be used, as Ban Tha Sai has been affected by the flood protection works recently implemented along the Lower Nam Mae Lao and its series is therefore inhomogeneous.

Using the existing annual maximum series of Ban Pong Pu Fuang EV1 and GEV distributions has been applied to fit the observed distribution of extremes. The results are presented in Table 4-1 and shown in Figure 4-10. It is observed that the GEV distribution fits better to the data then the EV1 distribution, though the value of the shape parameter of the GEV is still too small to be statistically significant from zero. Nevertheless, preference is given to GEV in this case.

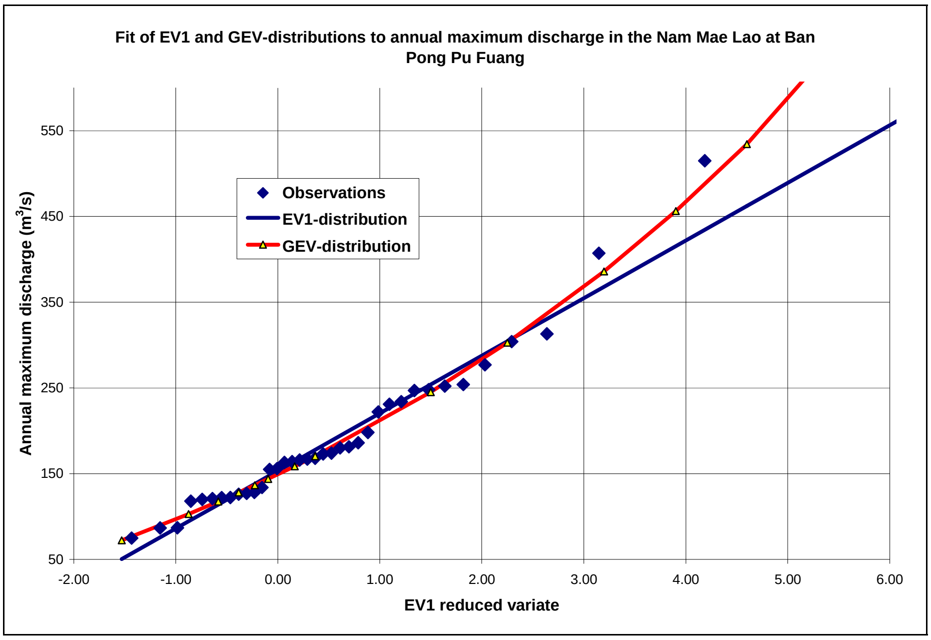

Figure 4-10 Fit of EV1 and GEV-distributions to annual maximum discharge in Nam Mae Lao at Ban Pong Pu Fuang, period 1971-2007.

As for the Nam Mae Kok at Ban Pong Na Kham, a correction has to be applied to account for differences between instantaneous peak discharges and daily averages. From the available instantaneous peak values a correction of 10% to the daily averages is required.

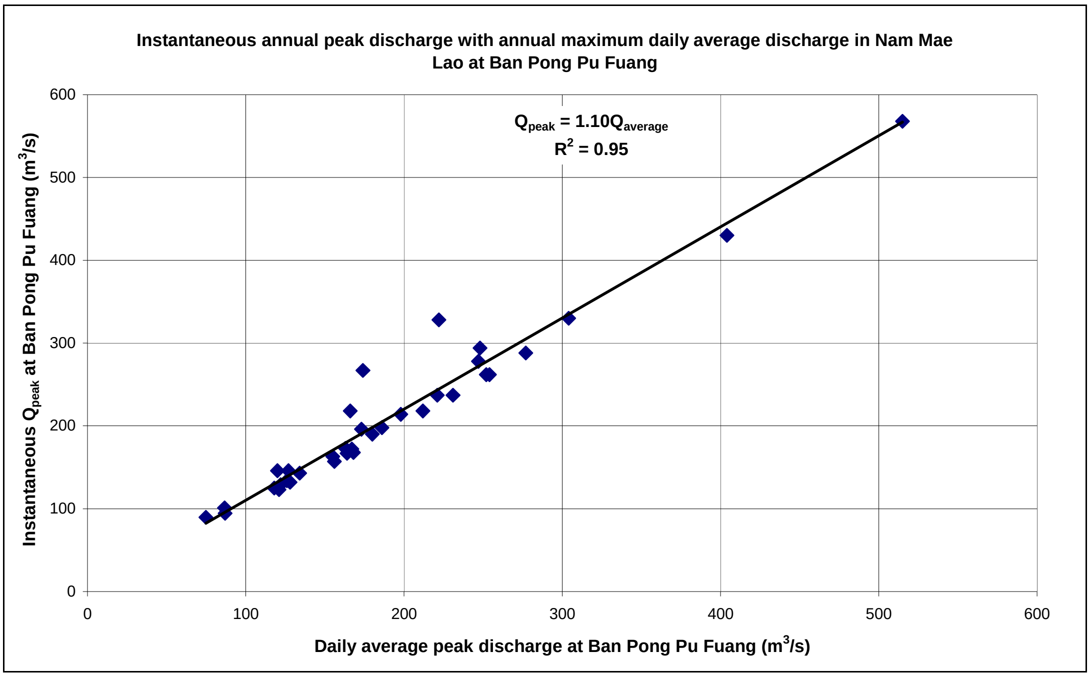

Figure 4-11 Comparison of instantaneous peak discharge and annual maximum daily average discharge in Nam Mae Lao at Ban Pong Pu Fuang, period 1971-2005.

Some 85% of the peaks on the Nam Mae Lao occur in the months August and September, with 7 September as the average occurrence date. Occasionally, peaks occur in June/July and in November. There is no relation between the peak size and the day of occurrence of the peak.

Flood volume and flood shape

For estimation of the flood duration the flood volume and flood hydrographs of the Nam Mae Lao at Ban Pong Pu Fuang have been investigated. The relation between flood volume and peak flow has been derived from the annual maximum flow at Ban Pong Pu Fuang and the flood volume from 15 days before till 15 days after the occurrence of the peak. The relation is shown in Figure 4-12. The standard error of the presented relation is 55 MCM.

The shapes of the flood hydrographs have been derived from the shapes of the 20 largest annual floods in the Nam Mae Lao. The procedure to get the 5%, 10%, etc. hydrograph shapes has been explained in Section 4.2. Examples of lean, medium and wide hydrographs are shown in Figure 4-13. It is observed that for a median flood wave typically 50% of the peak value is exceeded from 2 days prior to the peak to 3 days after the peak, i.e. not very flashy, though it is also seen that the lean floods in Lao have a rather flashy character.

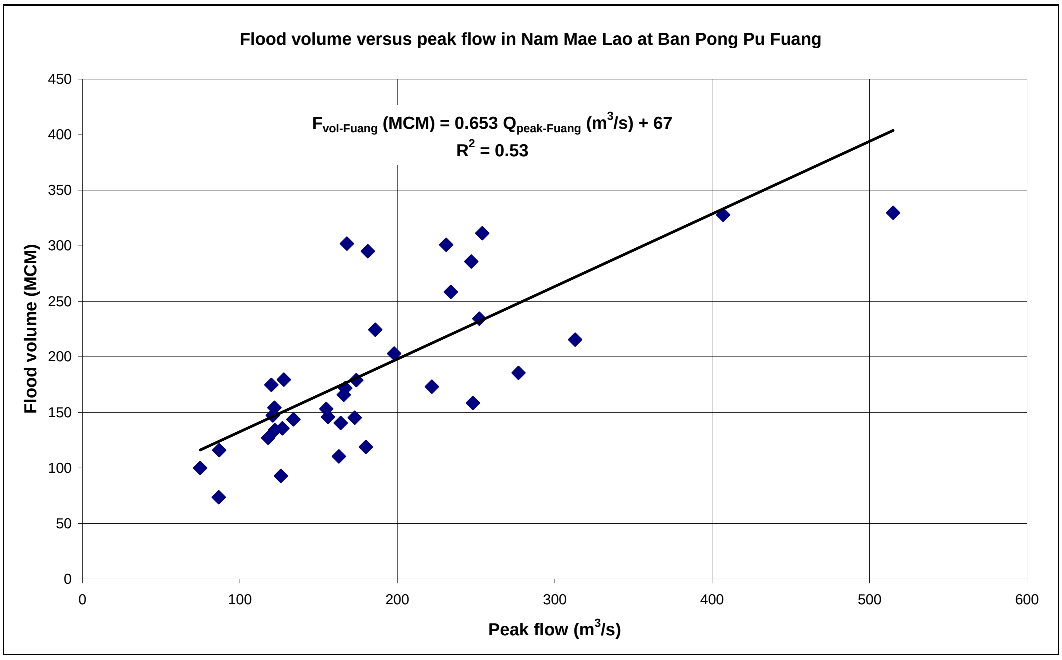

Figure 4-12 Flood volume versus peak flow in Nam Mae Lao at Ban Pong Pu Fuang.

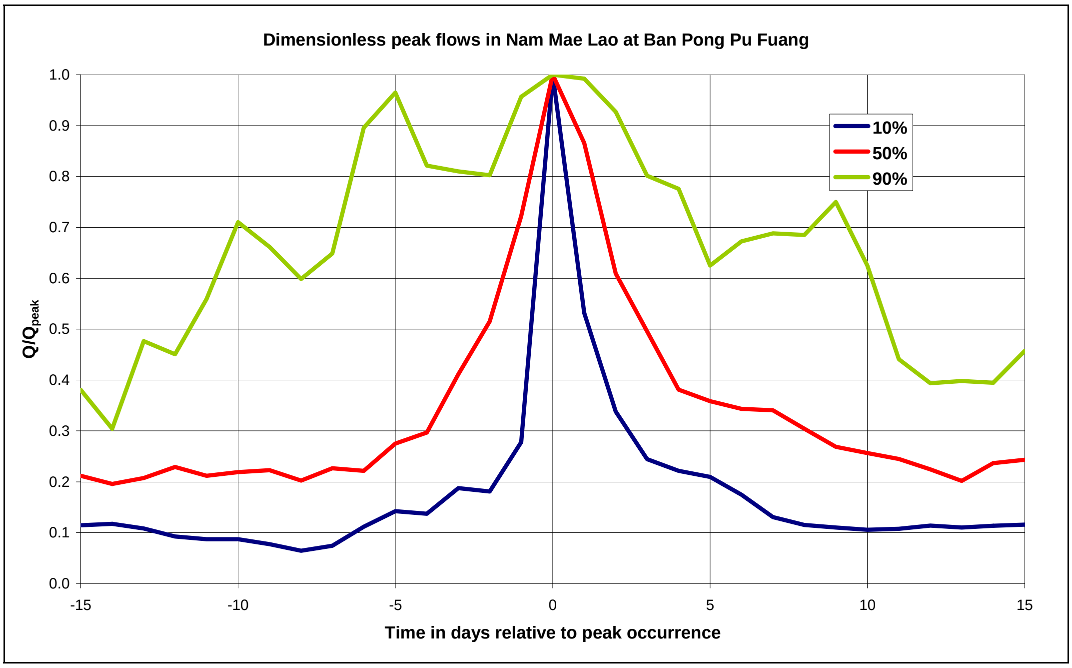

Figure 4-13 Example of dimensionless hydrographs in Nam Mae Lao at Ban Pong Pu Fuang.

Lateral inflow

For calculating the flood levels along the Nam Mae Lao in the Chiang Rai region the conditions in the Nam Mae Korn have to be available as well as the flow over the Chiang Rai Weir from the Nam Mae Kok.

The flow of the Nam Mae Korn as used by Kittipong (2009) as discussed in Section 4.2 was found not suitable. The proposed procedure presented in that section is to be applied here as well.

The peak flow in the Nam Mae Lao and the flow in the Nam Mae Kok at the time of the Lao peak hardly correlate. The flow volume in the Nam Mae Kok during the passage of the peak hydrograph in the Nam Mae Lao, however, correlates better as shown in Figure 4-14. Once the volume in the Nam Mae Kok is determined from the flood volume in the Nam Mae Lao a corresponding flow value in the Nam Mae Kok when the peak passes Ban Pong Pu Fuang is obtained from Figure 4-15.

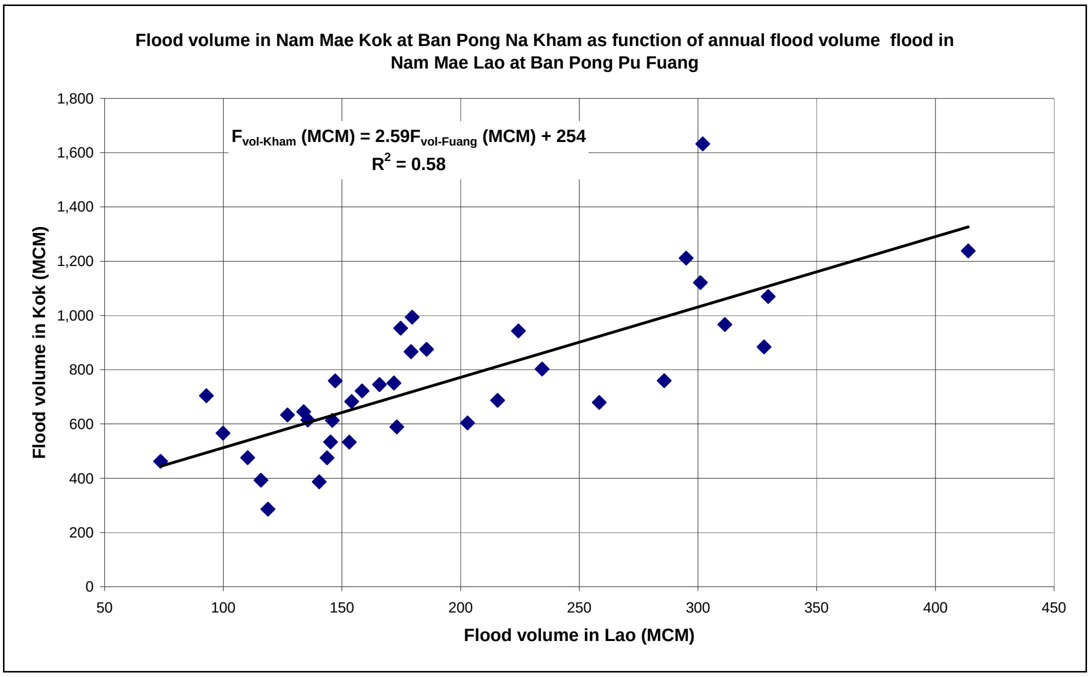

Figure 4-14 Flow volume in Nam Mae Kok at Ban Pong Na Kham during occurrence of peak flow in Nam Mae Lao.

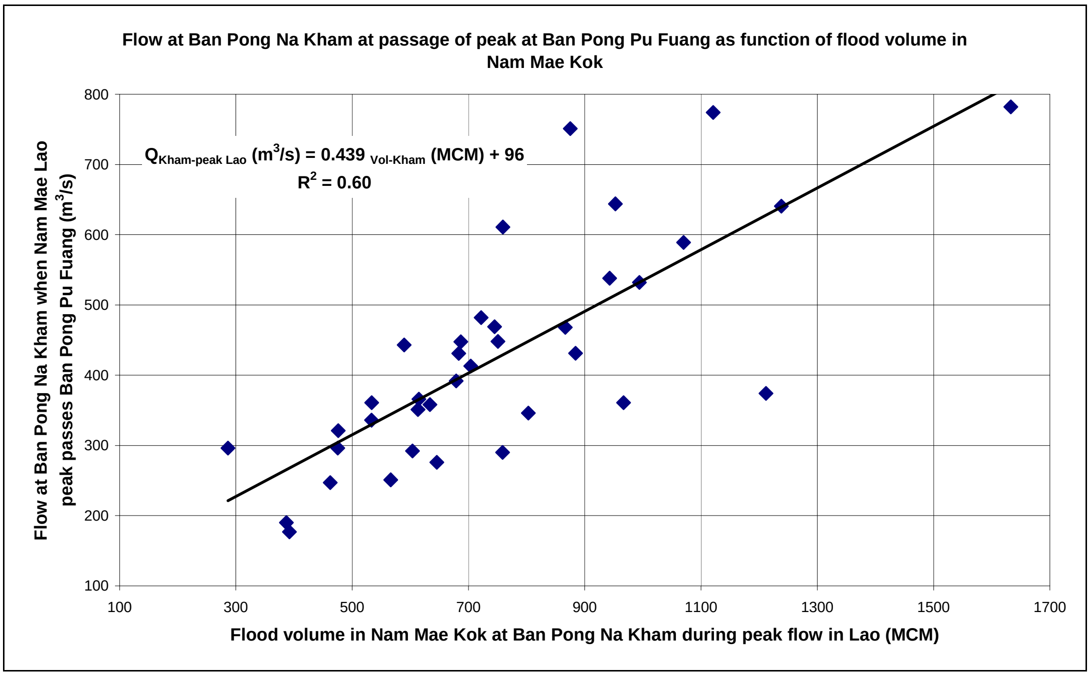

Figure 4-15 Flow in Nam Mae Kok when peak in Lao passes Ban Pong Pu Fuang as function of flow volume in Nam Mae Kok.

By using the flood hydrograph shapes for the Nam Mae Kok as derived in Section 4.2 with the above derived “peak”-flow and flow volume in the Kok the boundary at Ban Pong Na Kham is known. From Ban Pong Na Kham till Chiang Rai Weir a lateral inflow of 0.029 times the flow at Ban Pong Na Kham is to be applied. Between the Lao-Kok confluence and Ban Mae Phaeng a lateral inflow equal to 0.113 times the sum of the flow from the Kok at Chiang Rai Weir, the Lao at confluence and the flow from the Korn is applied and from Ban Mae Phaeng to the Mekong 0.027 times the said sum.

Downstream boundary

Since the Mekong does not create backwater on the Kok at the Lao confluence a constant water level may be assumed at the Kok mouth.

Morphology

The water levels at Ban Pong Pu Fuang for a discharge of 250 m^3/s have varied historically with about 1.90 m. Relative to the model calibration period the levels for this discharge has been 0.70 m higher to 1.20 m lower. This effect is to be included by adjusting the calibrated Manning n.

4.4 Nam Mae Kok d/s Nam Mae Lao confluence

General

The flood levels in the Nam Mae Kok d/s of the Nam Mae Lao confluence but upstream of the backwater reach of the Mekong are determined by the discharge and the conveyance capacity of the river. The discharge series of the Nam Mae Kok downstream of the Nam Mae Lao confluence can be derived from the sum of the series of Ban Pong Na Kham (1966-2007) on the Kok and of Ban Pong Pu Fuang (1971-2007) on the Lao, corrected for area, resp. 1.041 and 1.268. By adding the two discharges time series account is given to non-coincidence of peaks on the two rivers. In this way a discharge series covering the years 1971 to 2007 is created. (Note that in view of uncertainties in the Korn record, its possible relative larger contribution to the Kok flow has been discarded)

In this section of the river Kok since 1994 station Ban Mae Phaeng has also been in operation, and controls a drainage area of 10,474 km^2 (for comparison: at the Kok/Lao confluence the drainage area equals 9,410 km^2). However, a comparison of the combined Kok and Lao series with the latter reveals that the flow in the Nam Mae Kok as observed at Ban Mae Phaeng with a few exceptions highly overestimates the discharge of the Nam Mae Kok. For 1996 the adjusted sum of the flow at Ban Pong Na Kham and Ban Pong Pu Fuang is in close agreement with the series of Ban Mae Phaeng. But for most other years there is a grave inconsistency, compare e.g. Figure 4-16 with Figure 4-17. In Figure 4-18 the result of a double mass analysis on the daily flow in the Nam Mae Kok at Ban Mae Phaeng and at Lao confluence is presented: a significant deviation from a straight line is observed. As mentioned in Section 4.2 the Ban Mae Phaeng series has been used by Kittipong (2009) to scale the SWAT-runoff for lateral inflow to the hydraulic model. Generally, for the entire period 1994-2007 the flow at Ban Mae Phaeng is 25% too large.

The above observations imply that Kittipong (2009) applied a lateral inflow which is 2.3 times the required inflow. This explains the unrealistic lateral inflow for the Nam Mae Korn as discussed in Section 4.2. Also, by calibration on observed water levels it follows that the Manning roughness values in this reach of the river have been underestimated by overestimating the discharge.

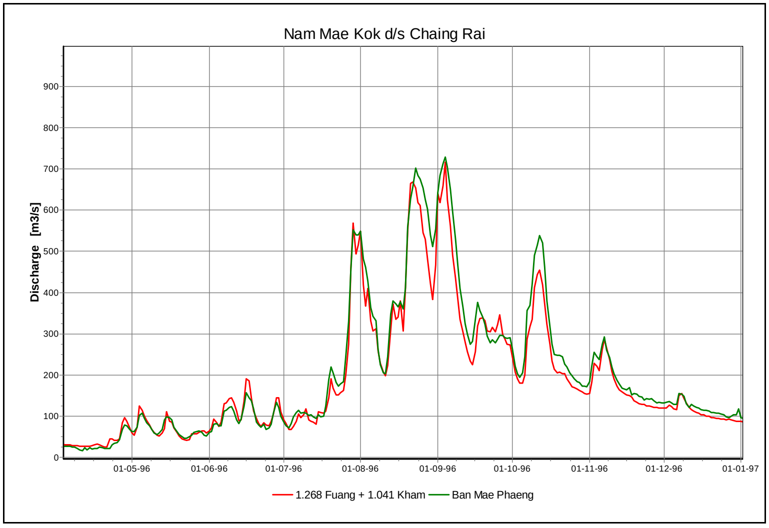

Figure 4-16 Nam Mae Kok at Lao confluence and at Ban Mae Phaeng, year 1996.

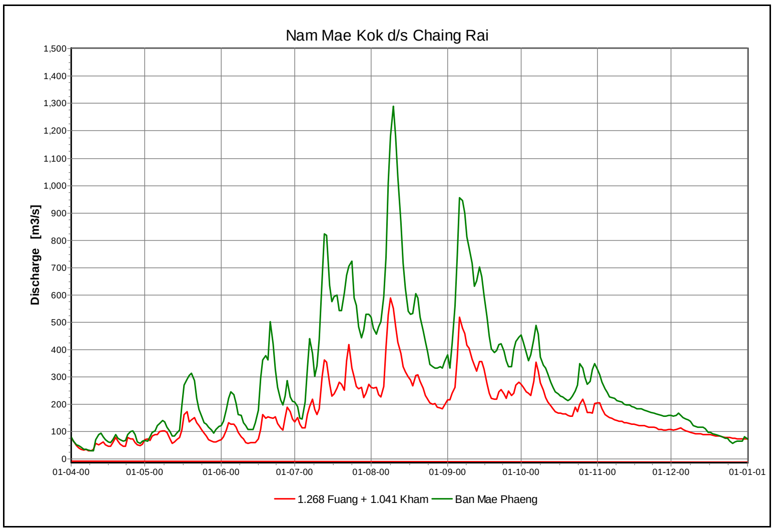

Figure 4-17 Nam Mae Kok at Lao confluence and at Ban Mae Phaeng, year 2000.

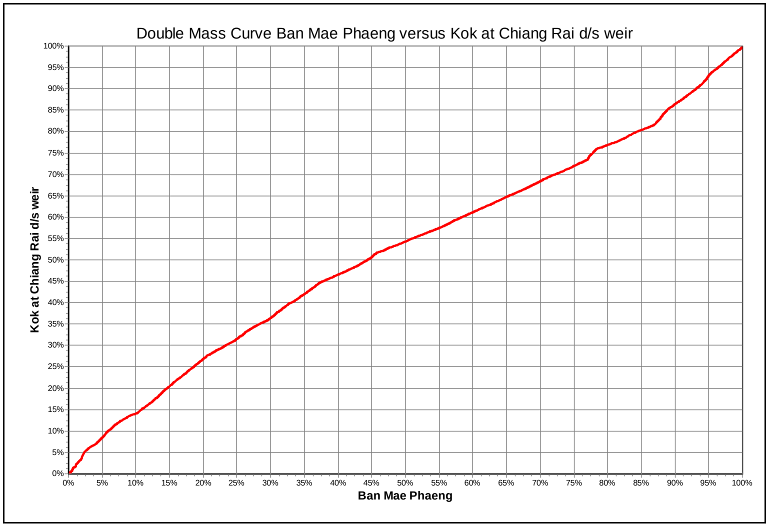

Figure 4-18 Double mass curve of discharge in Nam Mae Kok at Ban Mae Phaeng and at Lao confluence for years 1994-2007.

Peak discharge

In view of above discussed validation, the Ban Mae Phaeng series was discarded and the annual maximum daily discharge for the Nam Mae Kok downstream of Chiang Rai Weir has been extracted from the combined Kok and Lao series at Lao confluence. These series are compared with those at Ban Pong Na Kham and Ban Pong Pu Fuang in Figure 4-19. A strong correlation with the peaks at Ban Pong Na Kham is observed from Figure 4-20. The combination leads to 39% higher values downstream of the Lao confluence on average than observed at Ban Pong Na Kham. Estimates are based on the increase of area, (see Section 4.5.3) a 42% higher value at the confluence than in Ban Pong Na Kham is calculated.

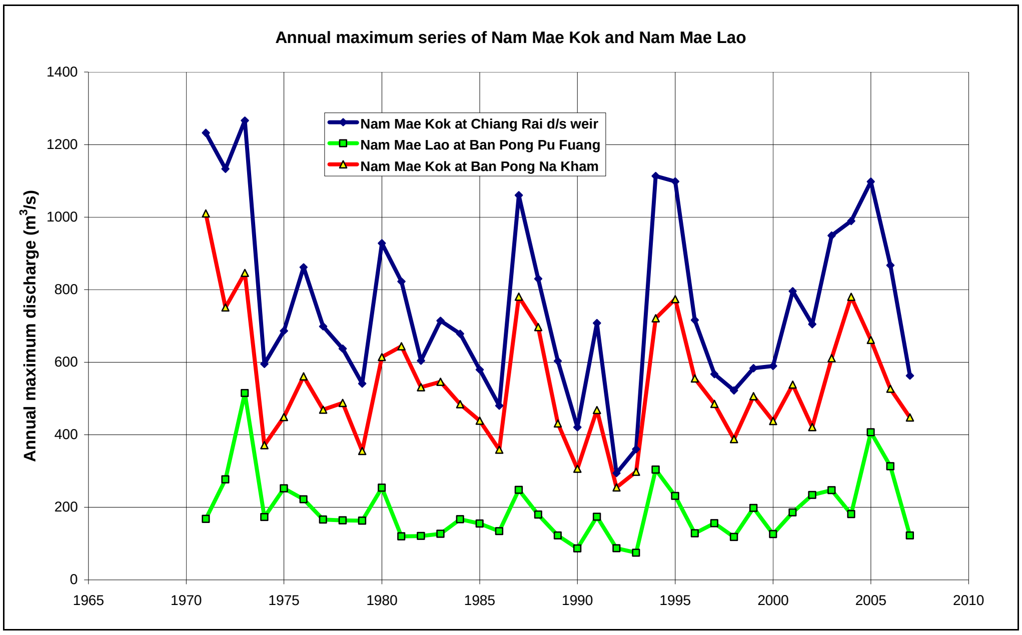

Figure 4-19 Annual maximum series of daily average discharge in Nam Mae Lao at Ban Pong Pu Fuang and Nam Mae Kok at Ban Pong Na Kham and at Lao confluence.

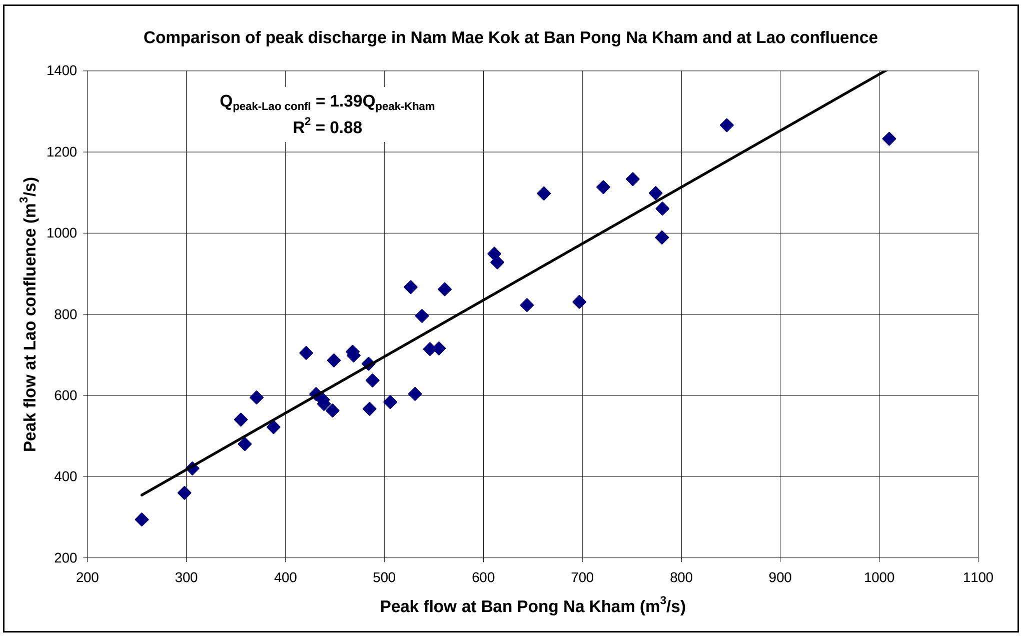

Figure 4-20 Comparison of annual maximum daily average discharges in Nam Mae Kok at Ban Pong Na Kham and at Loa confluence.

The fit of the EV1 and GEV-distributions to the annual extremes for the Nam Mae Kok at Lao confluence is presented in Figure 4-21. Best fit is obtained with the GEV-distribution, though the k = 0 hypothesis for applicability of EV1 is not rejected at a 5% significance level. The numerical results are presented in Table 4-1.

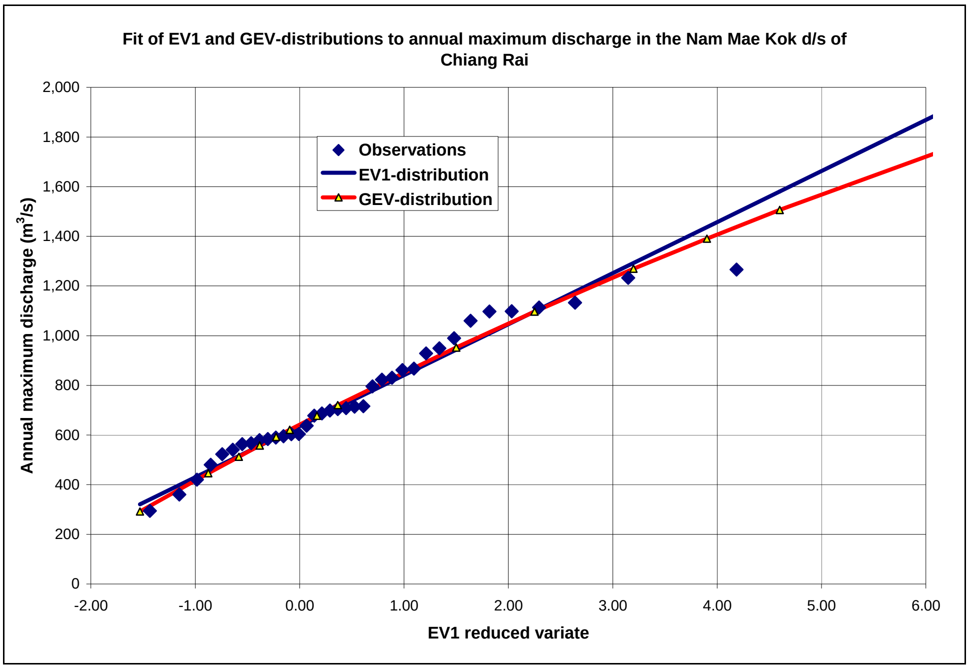

Figure 4-21 Fit of EV1 and GEV-distributions to annual maximum discharge in Nam Mae Kok downstream Chiang Rai Weir and Nam Mae Lao confluence, period 1971-2007.

It may also be observed from the table that discharge for a distinct return period from this combined series is smaller than the sum of the discharge extremes of the individual contributions, indicating that peak discharges on the two rivers may not occur on the same day. The differences between the sum of the individuals and the combined series according to the GEV-distributions are shown in Figure 4-22 as a function of the return period.

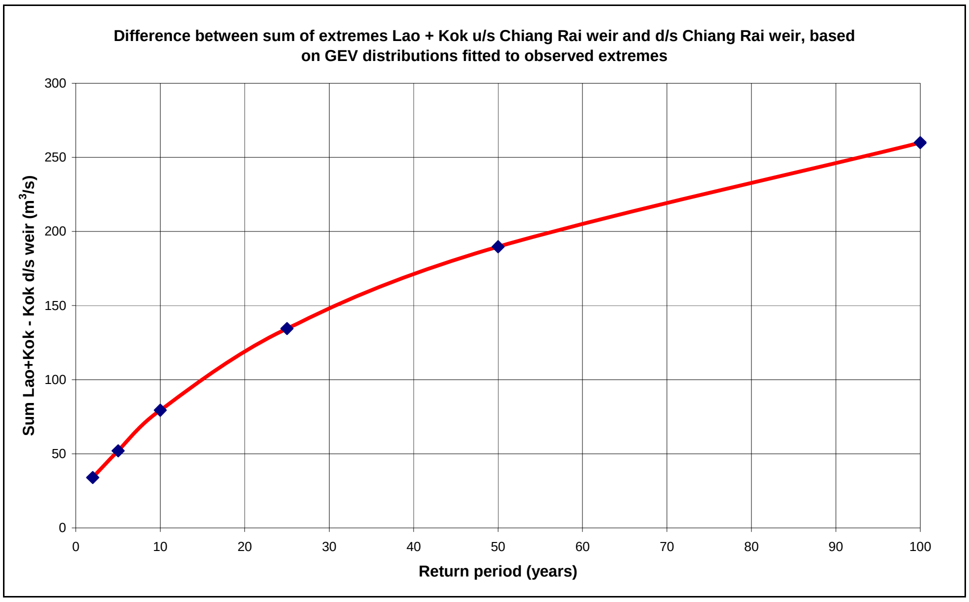

Figure 4-22 Reduction of combined peak discharge d/s Chiang Rai relative to sum of upstream Kok and Lao peaks as a function of return period.

Flood volume and flood shape

Flood volume and hydrographs shape that have been analysed are similar to the Nam Mae Kok upstream of the Lao confluence and the Nam Mae Lao to determine flood duration and related damages. The flood volume refers to the volume from 15 days prior to 15 days after the annual maximum peaks. The flood volume as a function of the flood peak is shown in Figure 4-23. The standard error of estimate of the relation is 190 MCM. Characteristic shapes of lean, medium and wide hydrographs are shown in Figure 4-24.

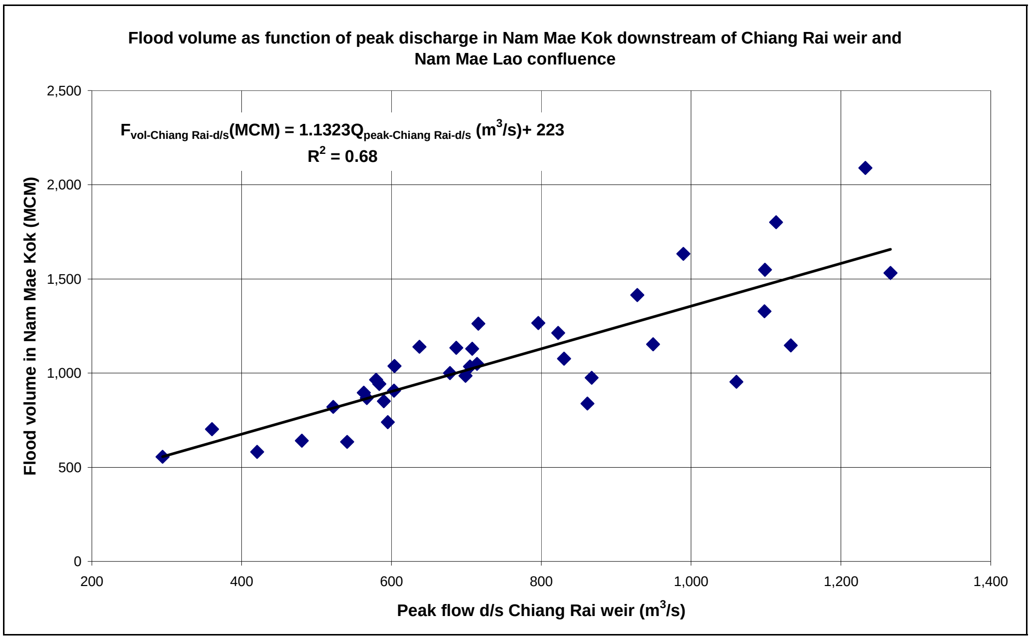

Figure 4-23 Flood volume versus peak flow in Nam Mae Kok at Lao confluence.

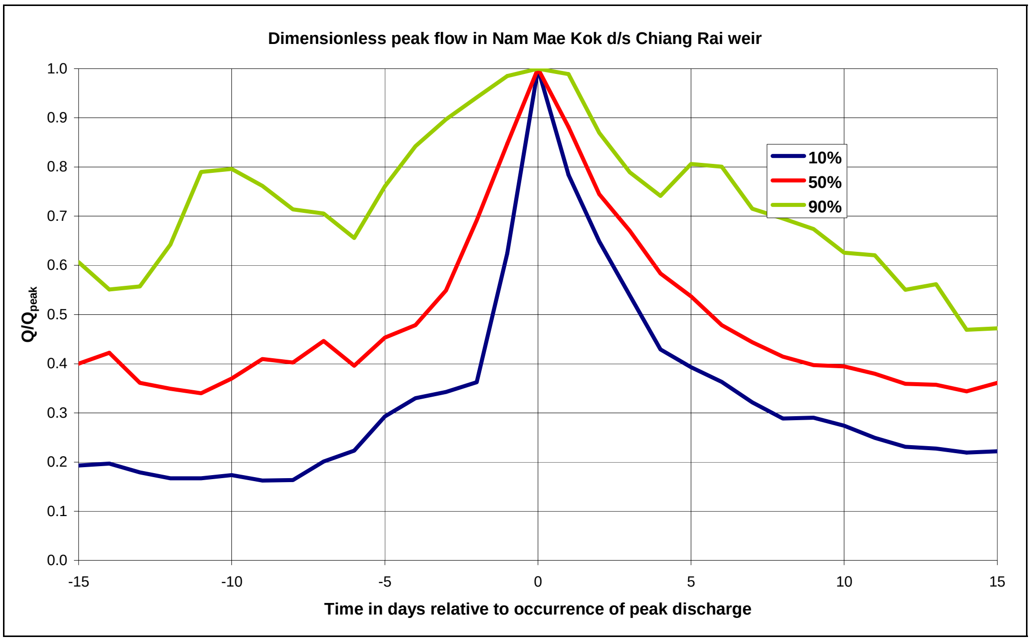

Figure 4-24 Example of dimensionless hydrographs in Nam Mae Kok at Lao confluence.

Lateral inflow

The lateral inflow downstream of the Lao confluence can be taken in proportion to the added area, similar to the procedure proposed in Section 4.3: between the Lao-Kok confluence and

Ban Mae Phaeng a lateral inflow equal to 0.113 times the flow at the confluence and from Ban Mae Phaeng to the Mekong River, 0.027 times the flow at the confluence is to be applied.

Downstream boundary

Since the Mekong does not create backwater on the Kok in the concerned reach a representative stage-discharge relation may be assumed in the Mekong at the Kok mouth, see Section 4.5, with an average Mekong regime at Chiang Saen.

4.5 Mekong - Nam Mae Kok confluence

At the confluence of the Nam Mae Kok with the Mekong the joint occurrence of water levels in the Mekong and discharge from the Nam Mae Kok at mouth determines the flood hazard. The components of this bivariate distribution will be elaborated in this section. The water levels in the Mekong at the Nam Mae Kok confluence can be obtained from station Sop Kok. However, this station is no longer in operation and the length of the series is too short for statistical analysis. But the water levels at Sop Kok correlate well with the nearby station Chiang Saen, which has been in operation since 1960. It implies that statistics of peak flows and flood volumes will be elaborated for station Chiang Saen and the results will be translated to Sop Kok using a stage-relation curve.

4.5.1 Mekong at Chiang Saen

A flow record for the period 1960-2006 is available for Chiang Saen, the first discharge station in the Lower Mekong basin. Annual maximum discharges and annual flood volume (period June-November) have been extracted from the series. The time-series of peaks and flood volumes is presented in Figure 4-25. The series do not show any trend; peak flow values are generally between 5,000 and 15,000 m^3/s, whereas the flood volumes range from 40,000 to 85,000 MCM on average. Only in 1966 and 1971 were these ranges substantially exceeded. From the graph it is observed that the peak flows and flood volumes are correlated. However, Figure 4-26 shows that for a particular peak discharge the flood volume, and consequently the flood duration, may vary considerably. In view of this, the bivariate distribution of peak flows and flood volume will be considered as well.

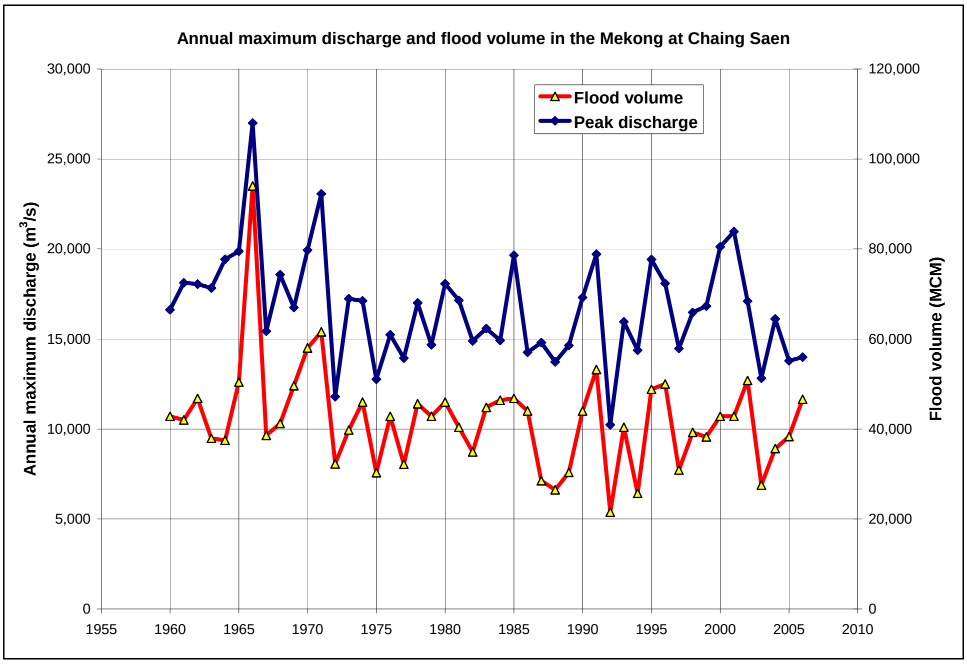

Figure 4-25 Annual maximum discharge and flood volume in the Mekong at Chiang Saen.

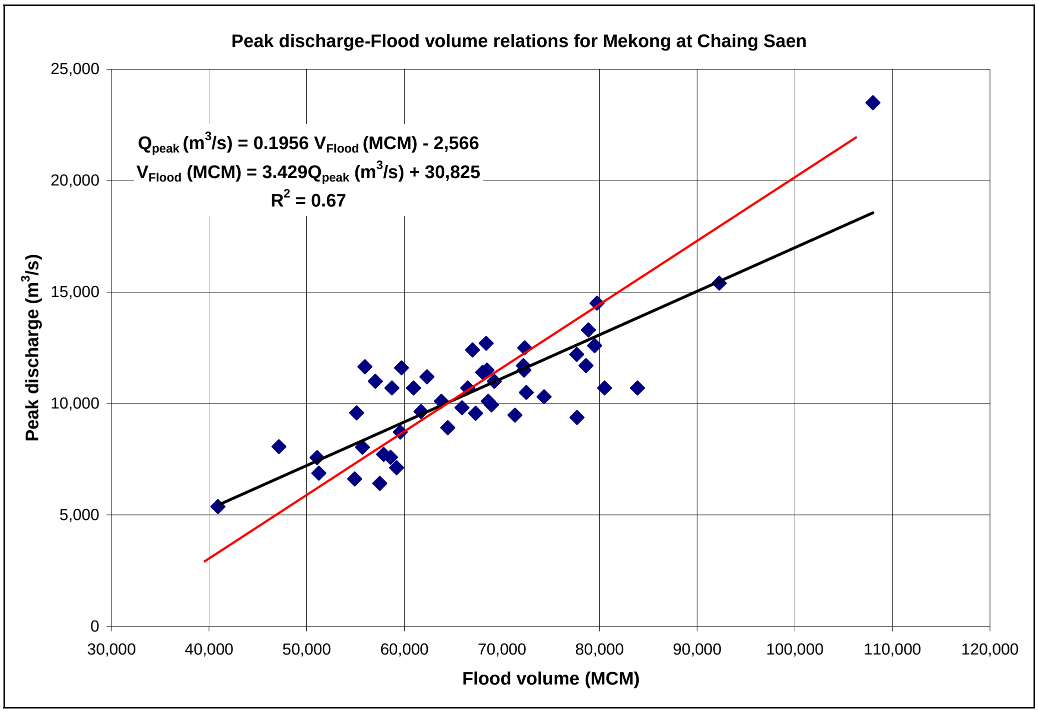

Figure 4-26 Peak discharge – Flood volume relations for the Mekong at Chiang Saen.

Peak discharge

The EV1 and GEV-distributions have been used to fit the observed distribution of annual maximum discharge in the Mekong at Chiang Saen. The computational results have been presented in Table 4-2 and are shown in Figure 4-27.

From the graph it is observed that both distributions fit reasonably, but the value for the year 1966 is an extreme outlier; its return period according to EV1 and GEV amounts respectively 800 and 10,000 years.

Flood volume

Similar to the procedure for the annual maximum discharge the distribution of the annual flood volume (flow volume in the period 1 June – 30 November) has been fitted to EV1 and GEV-distributions. The parameters and flood values for selected return periods are presented in Table 4-2, and graphically displayed in Figure 4-28. Like for the annual maximum discharge here also the EV1 as well as the GEV functions fit to the observed flood volume distribution. The latter distribution leads to lower values of flood volumes for the selected return periods.

Table 4-2 EV1 and GEV-parameters of peak-discharge (m^3/s) and flood volume (MCM) distributions and values for distinct return periods in the Mekong at Chiang Saen and Nam Mae Kok near the mouth.

Parameter	Peak discharge in Mekong (m^3/s)	Flood volume in Mekong (MCM)	Peak discharge Nam Mae Kok (m^3/s)	Flood volume Nam Mae Kok (MCM)
years	1960-2006	1960-2006	1971-2007	1971-2007
		EV1		
α	2,126	9,895		849.3
u	9,289	61,173		3,685
T (years)				
2	10,068	64,800	784	3,997
5	12,478	76,015	1,041	4,959
10	14,074	83,440	1,211	5,597
25	16,090	92,823	1,426	6,402
50	17,585	99,783	1,585	6,999
100	19,070	106,692	1,743	7,592
		GEV		
k	0.096	0.1108		0.049
α	2,307	10,854		886.5
u	9,387	61,701		3,705
T (years)				
2	10,217	65,599	795	4,027
5	12,608	76,701	1,050	4,987
10	14,054	83,320	1,210	5,595
25	15,737	90,933	1,400	6,331
50	16,890	96,087	1,534	6,856
100	17,960	100,820	1,661	7,360

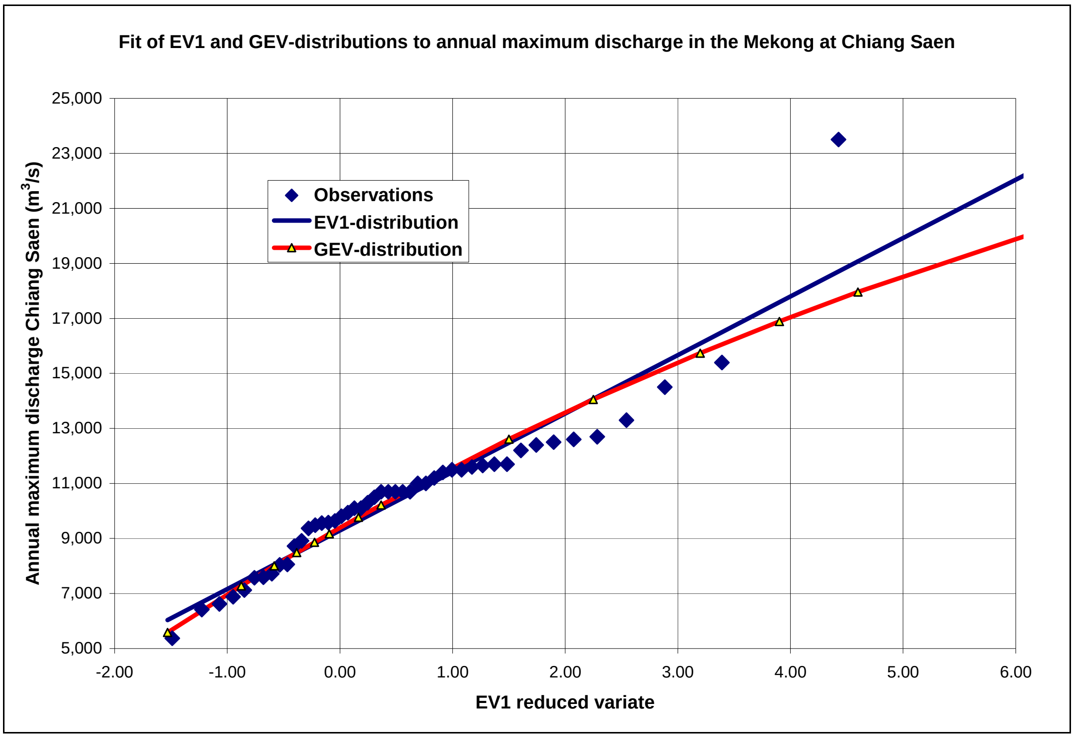

Figure 4-27 Fit of EV1 and GEV-distributions to annual maximum discharge in Mekong at Chiang Saen, period 1960-2006.

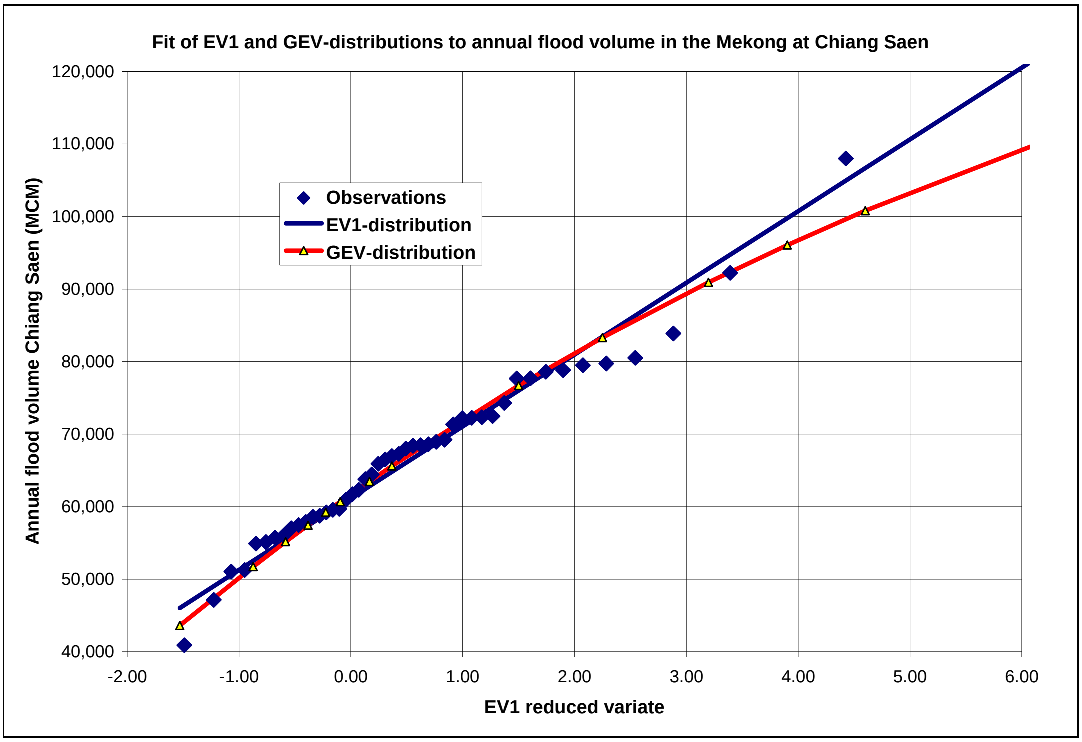

Figure 4-28 Fit of EV1 and GEV-distributions to annual flood volume (June-November) in Mekong at Chiang Saen, period 1960-2006.

Bivariate distribution of peak discharge and flood volume

The bivariate extreme value distribution of flood peaks and flood volumes has been described by Adamson et al. (1999). The joint probability can be generated by the Gibbs sampler Monte Carlo procedure. This technique requires that annual flood peaks (X) and annual flood volumes (Y) are regressed against each other (see Figure 4-26):

$$X = a_{x,y} + b_{x,y} Y$$
$$Y = a_{y,x} + b_{y,x} X \qquad (4.2)$$

and the GEV distributions are used to model the residuals of flood peaks and flood volumes with parameters respectively (u_x, α_x,,k_x) and(u_y, α_y,,k_y). The Gibbs procedure then reads with uniform distributed random numbers R and the generated values marked with #:

$$X_j^{\#} = a_{x,y} + b_{x,y} Y_j^{\#} + u_x + \frac{\alpha_x}{k_x}\left\{1 - (-\ln(R_1))^{k_x}\right\}$$
$$Y_{j+1}^{\#} = a_{y,x} + b_{y,x} X_j^{\#} + u_y + \frac{\alpha_y}{k_y}\left\{1 - (-\ln(R_2))^{k_y}\right\} \qquad (4.3)$$

The coefficients of the equations (4.2) and (4.3) and the distribution parameters are presented in Table 4-3. The fits to the residuals are shown in Figure 4-29 and Figure 4-30. It may be observed that in these cases only the GEV-distribution is applicable.

Table 4-3 Regression parameters and parameters of GEV distributions of regression residuals for the peak flows and flood volumes of the Mekong at Chiang Saen.

Regression	**Regression parameters**		**GEV parameters of regression residuals**		
Peak on volume	$a_{y,x}$=-2,566	$b_{y,x}$=0.1956	u_y= -491.3	α_y= 1,660	k_y=0.375
Volume on peak	$a_{x,y}$=30,825	$b_{x,y}$=3.429	u_x=-2,431	α_x=6,686	k_x=0.266

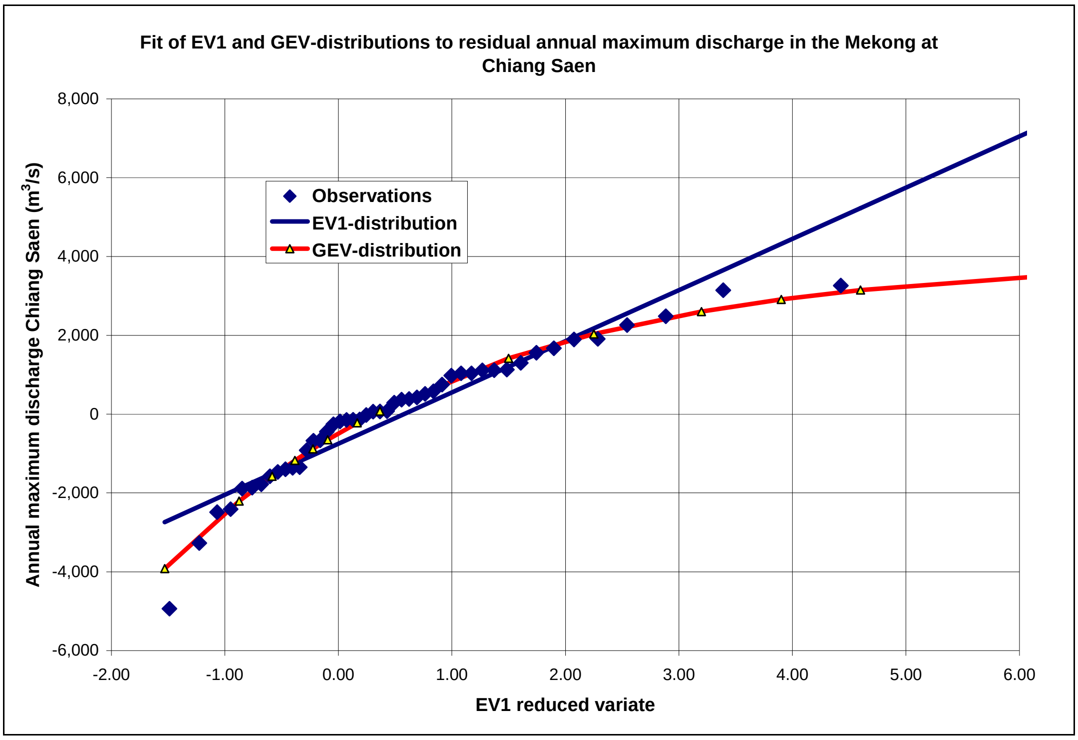

Figure 4-29 EV1 and GEV fit to residual annual maximum discharge in the Mekong at Chiang Saen.

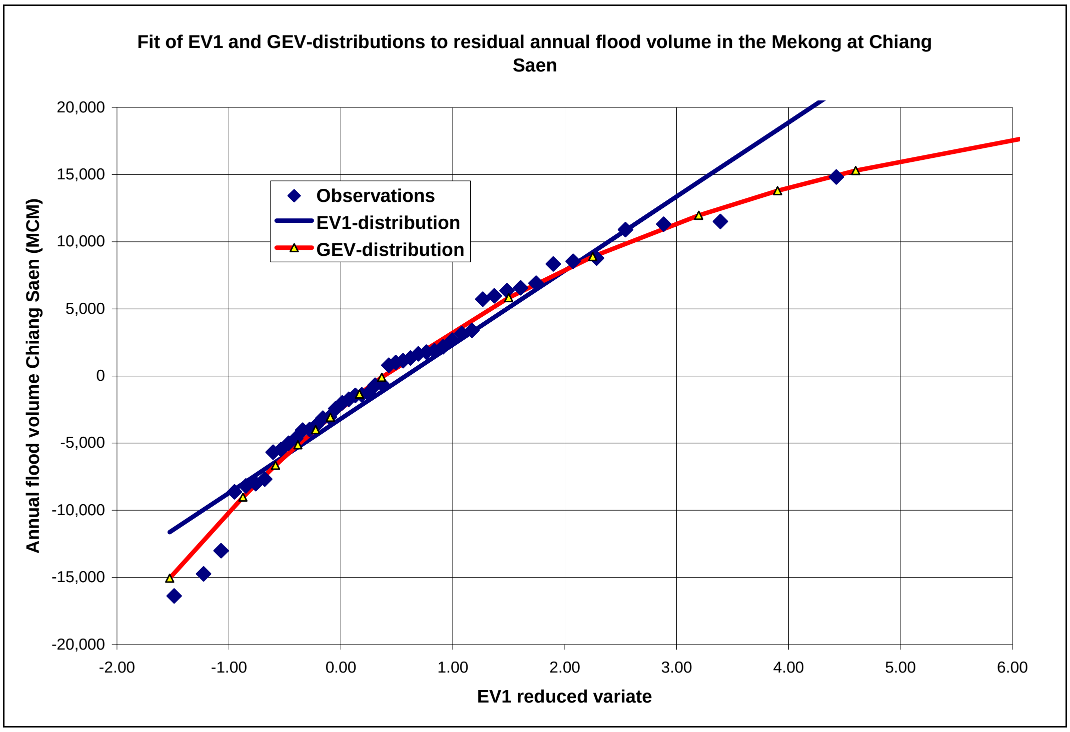

Figure 4-30 EV1 and GEV fit to residual annual flood volume in the Mekong at Chiang Saen.

4.5.2 Discharge rating at Sop Kok

The downstream boundary of the Mekong section of the hydraulic model should be a discharge rating. Since the model only extends up to Sop Kok a discharge rating for Sop Kok is to be included. Based on the available concurrent water level and discharge series for Sop Kok station (010601) the following stage-discharge relation applies:

$$\begin{aligned} &Q_{SopKok}(m^3/s) = 90.1 + 334.8h_{SopKok} + 130.85h^2_{SopKok} - 2.384h^3_{SopKok} \qquad h\ in\ (m+GZ) \\ &H_{SopKok}(masl) = h_{SopKok}(m+GZ) + 355.31 \end{aligned} \tag{4.4}$$

with: Q= discharge (m^3/s)

h = gauge reading relative to gauge zero

H = water level relative to MSL

Note that a stage-discharge boundary at Sop Kok is not ideal as the rating is determined due to backwater levels at the Kok mouth almost entirely for a given combined Mekong and Kok flow.

4.5.3 Nam Mae Kok at mouth

Station Sop Kok was located on the Mekong near the mouth of the Nam Mae Kok. The available discharge series for this station includes the flow of the Nam Mae Kok, and could basically be used in combination with Chiang Saen to estimate the flow from the rivers draining between the stations, namely Nam Mae Kham and Nam Mae Kok. However, the flows of the Kham and the Kok are small compared to the mainstream flows and hence the balance would give an inaccurate estimate of the lateral inflows. Therefore, an alternative procedure described below is advocated.

Peak discharge

The distribution of annual maximum discharge of the Nam Mae Kok at mouth is derived from the distribution downstream of Chiang Rai corrected for drainage area (A). Following Adamson (2007), in the Nam Mae Kok environs annual peak values are proportional to A$^{0.75}$. Hence an area factor of (10,730/9,410)$^{0.75}$ = 1.103 has been applied to the annual extremes just downstream of Lao confluence (as presented in Table 4-1). The values (for selected return periods) have been included in Table 4-2.

Flood volume

Similarly, EV1 and GEV distributions have been fitted to the annual flood volumes in the Nam Mae Kok at mouth. The flood volumes have been derived from the flow series determined for the Nam Mae Kok at Lao confluence multiplied by the ratio of their respective drainage areas (= 1.14). The results are presented in Table 4-2 and shown in Figure 4-31. From the latter it is clear that both distributions fit the observations.

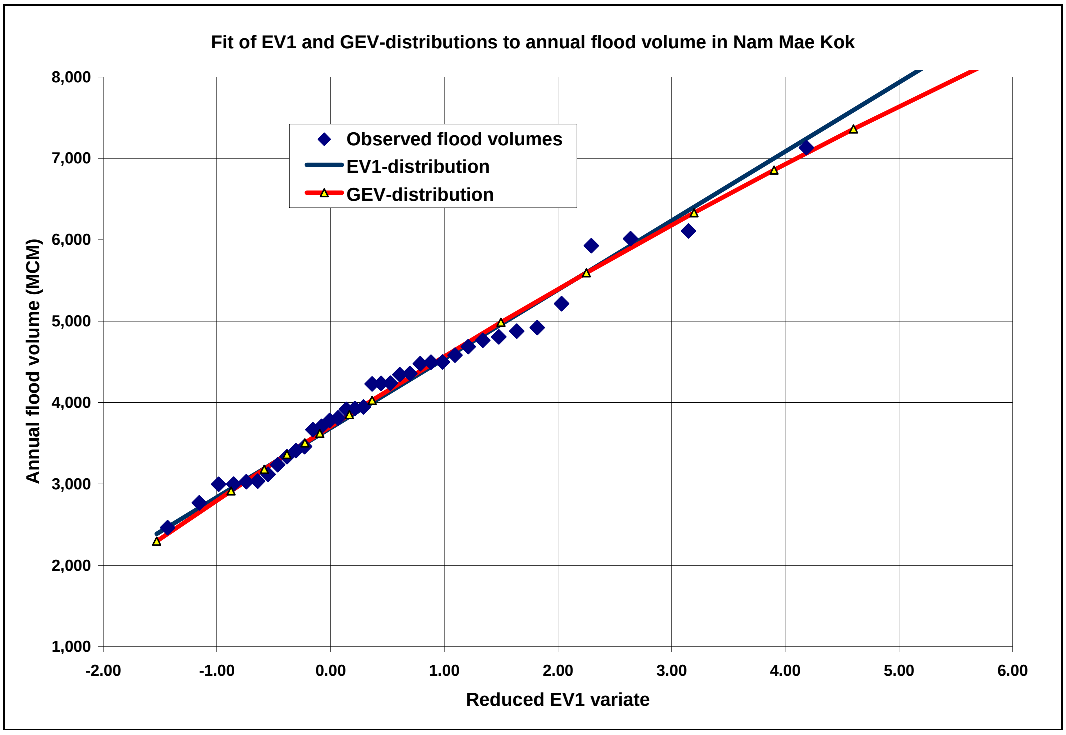

Figure 4-31 Fit of EV1 and GEV-distributions to annual flood volume in Nam Mae Kok at mouth, period 1971-2007.

4.5.4 Correlation between flood peaks and volumes in Nam Mae Kok and Mekong

Peak flow and flood volumes of the Nam Mae Kok at mouth have been compared with the same variables on the Mekong to assess possible correlation between the variables for Monte Carlo simulations.

Peak flows

Annual peak discharges on Mekong at Chiang Saen and in the Nam Mae Kok downstream of Chiang Rai appear to be uncorrelated, as can be observed from Figure 4-33.

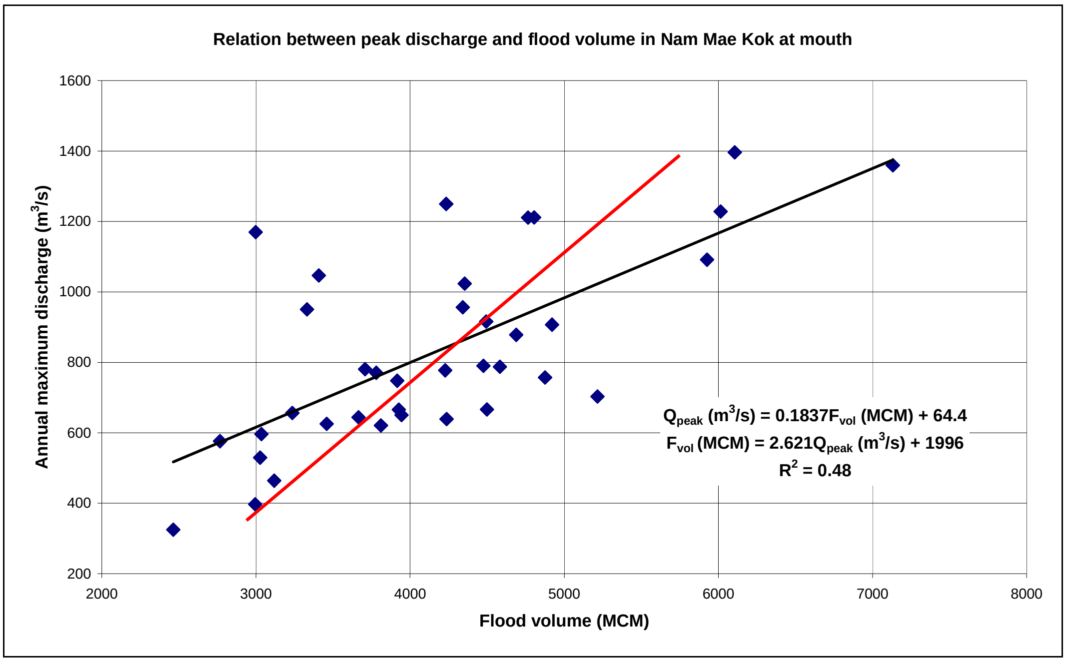

Figure 4-32 Relation between peak discharge and flood volume in Nam Mae Kok at mouth.

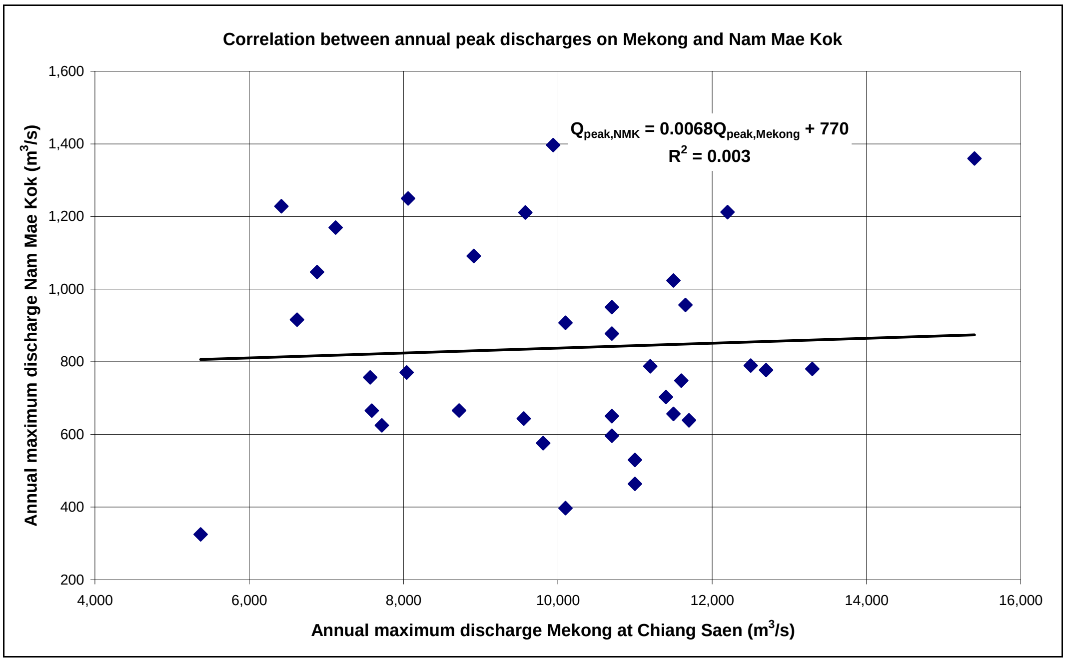

Figure 4-33 Relation between annual peak flows on Mekong and Nam Mae Kok.

The distribution of the date of occurrence of the annual peak values in the Mekong at Chiang Saen and the Nam Mae Kok downstream of Chiang Rai is presented in Figure 4-34. It is seen that on average the Nam Mae Kok peaks about 2 weeks later than the Mekong at the junction of the two rivers, which complies with Figure 3-24.

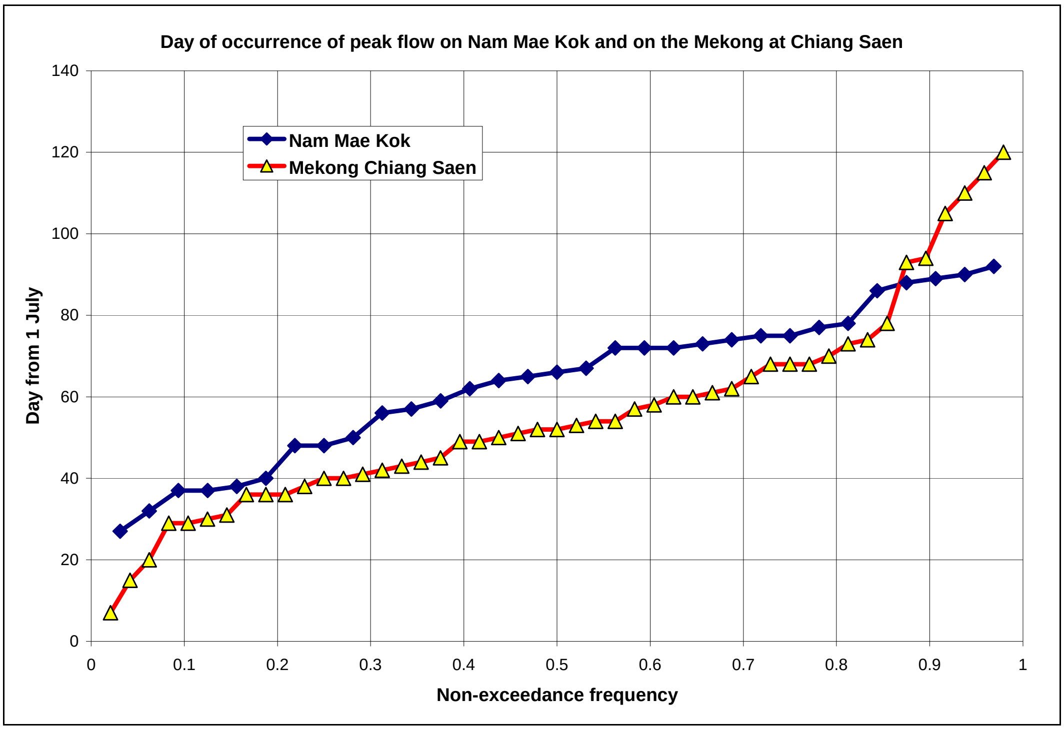

Figure 4-34 Occurrence of annual maximum discharge in Mekong at Chiang Saen and in Nam Mae Kok downstream of Chiang Rai.

Flood volumes

Similar to the flood peaks, the annual flood volumes in the Mekong and Nam Mae Kok also appear not to be correlated, as can be observed from Figure 4-35. This leads to extra combinations of hydrographs on the Mekong with discharge hydrographs in the Nam Mae Kok for Monte Carlo simulations.

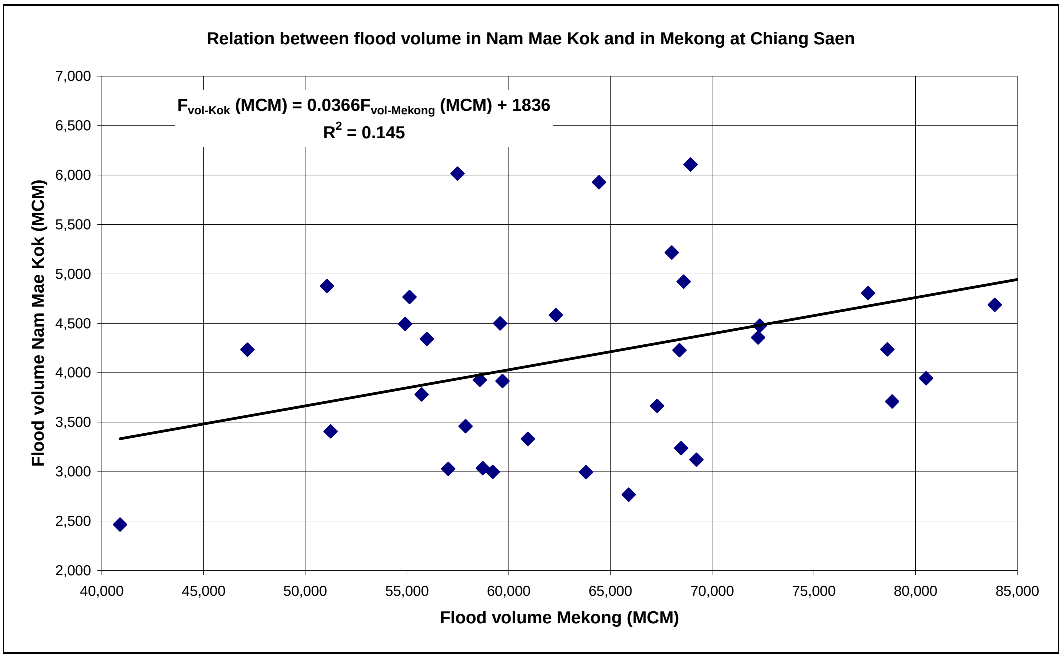

Figure 4-35 Relation between annual flood volumes in Mekong at Chiang Saen and Nam Mae Kok.

CHAPTER 5

FLOOD HAZARD

5 FLOOD HAZARD

5.1 General

From the previous chapters it can be deduced that for the transformation of the hydrological hazard into flood hazard to identify the flood extent and duration the hydraulic model should include at least the following branches and floodplains of the Nam Mae Kok:

- Nam Mae Kok from Ban Pong Na Kham up to the river mouth at Sop Kok,
- Nam Mae Lao from Ban Pong Pu Fuang to the river mouth at Chiang Rai, and
- Floodplains inundated by above mentioned rivers.

The boundary conditions of the hydraulic model include (see also Chapter 4):

3. for flood hazard assessment around Chiang Rai:
    - 3.a Nam Mae Kok upstream Lao confluence: discharge hydrographs at Ban Pong Na Kham on Nam Mae Kok (peaks from 2 to 100 year return period and volumes ranging from very low, low, medium, high to very high) with related hydrograph on as input for the Monte Carlo technique;
    - 3.b Nam Mae Kok downstream of Chiang Rai: discharge hydrographs based on an area adjusted sum of Ban Pong Na Kham and Ban Pong Pu Fuang flows (similar to 1.a) as input for the Monte Carlo technique;
    - 3.c Nam Mae Lao/ upstream of confluence with Nam Mae Kok: discharge hydrographs on Nam Mae Lao (Korn derived from Lao) at Ban Pong Pu Fuang (similar to 1.a) with related hydrograph on Nam Mae Kok as input for the Monte Carlo technique.
4. for flood hazard assessment near Nam Mae Kok mouth: selection of combination of discharge hydrographs of Mekong at Chiang Saen and a discharge rating at Sop Kok and discharge hydrographs of Nam Mae Kok as input for the Monte Carlo technique.

The hydraulic model and the boundary conditions are elaborated further in this chapter.

5.2 Hydraulic model

A 1D mathematical hydraulic model of the Nam Mae Kok and Nam Mae Lao has been developed by DWR/TNMC in 2006 for the Case Study: “Flood/Drought for Kok River Basin”. This model was embedded in a modelling framework with the SWAT rainfall-runoff model and the IQQM water demand model. The quality of the hydraulic model was considered to be insufficient for reliable flood hazard assessment in the Chiang Rai Region. Additional bathymetric surveys were required to improve the model simulation results. In the frame of the project ‘Strengthening of Flood Management capacity for the Kok River in Chiang Rai Province” of TNMC/DWR this upgrading has been recorded. The project included establishment of new gauging stations and topographic surveys. The surveys originally comprised 60 cross-sections of river and floodplain and additional 30 cross-sections of the river, all along the main stem from Chiang Rai to the river mouth. Recently, the surveys have been extended to the Nam Mae Lao and the Nam Mae Korn. In January 2009 a report containing the development, calibration, verification and application of the new hydraulic model of the Kok became available (Kittipong, 2009). In addition to the 1D hydraulic model also a 2D model of the region has also been established by the MRCS modelling team, including the floodplain and urban area. Though a 2D approach for the floodplain is very much welcomed, a 2D approach for the rivers with small cross-sections leads to very high requirements on computational grid size and consequently creates inherent inaccuracies. A 1D/2D approach would have been a far better choice (i.e. 1D for the rivers and 2D for the floodplain) and is strongly advocated by consultants as the flooding in the Chiang Rai Region is considered to be very complex.

Schematisation

The Kok hydraulic model includes the major rivers floodplains and structures of the Nam Mae Kok from upstream Chiang Rai to the Mekong as follows, see also Table 5-1.

1. Nam Mae Kok from Ban Pong Na to Sop Kok with a length of 90.65 km, including the Chiang Rai Weir at km 21.70 and outlets of:
   - 1.a Korn-Kok Diversion Canal (km 10.05);
   - 1.b Nam Mae Korn (km 19.70);
   - 1.c Nam Mae Lao (km 22.7).
2. Nam Mae Lao from Ban Pong Pu Fuang to mouth with a length of 69.01 km. It includes 3 weirs.
3. Nam Mae Korn from 14 km d/s of station Ban Pang Rim Korn (G4) to mouth with a length of 22.41 km, including the 4 weirs and the Korn-Kok Diversion Canal at km 5.95.
4. Korn-Kok Diversion canal with a length of 4.21 km as from 2005 onward.
5. Mekong from Chiang Saen to Sop Kok with a length of 5 km.

Surveyed river cross-sections have been provided from 3 sources:

- DWR;
- RID; and
- CRM (Chiang Rai Municipality).

The cross-sections prior to 2005 conditions included:

- 88 cross-sections for the Kok;
- 145 cross-sections for the Lao;
- 82 cross-sections for the Korn; and
- 19 cross-sections for the Mekong from the MRCS-Digital Atlas DEM.

For the situation from 2005 onward DWR carried out new surveys in 2008 particularly along the Korn and also on the Lao in view of embankment improvements above Chai Sombat Weir. The difference in cross-sectional areas along the Lao is depicted in Figure 5-1.

In 2007 DWR made a spot height map of the region including the floodplains comprising 390 elevations, which were transformed into a DEM. The GIS-layers were extended with information on streams, road networks, urban zones, water bodies land use and housing. The DEM has been used for the schematisation of the floodplain into storage cells connected with the river cross-sections via two-way weirs.

Schematisation

The boundary conditions comprised of discharge time series at the upper boundaries as derived from the observations at the hydrometric stations and lateral inflow from the hydrological model SWAT, calibrated to a water balance between the upper model boundaries and station Ban Mae Phaeng, midway from Chiang Rai and Sop Kok. As explained in Section 4.4 the series of Ban Mae Phaeng gives too high flows, hence consequently the lateral inflows are too high. It has been estimated that the lateral inflows are overestimated by a factor 2.3. Figure 5-2 shows all boundary nodes of the model, whereas Table 5-2 presents a brief description.

Table 5-1 Extent, stations and structures in the Nam Mae Kok hydraulic model.

River	**Location**		**Cross section data (m+MSL)**			**Weir characteristics**			
	Profile	**Distance (m)**	**Bed level**	**Left Bank**	**Right Bank**	**Height**	**Width**	**Crest**	**Type**
Kok	Pong Na Kham (Kok01)	0,000	400.01	410.85	405.65				
	Outlet Korn-Kok Canal (Kok11)	10,050	390.46	394.41	397.15				
	Mae Fa Luang Bridge (Kok17)	15,250	386.70	395.22	394.32				
	Chiang Rai Bridge (Kok23)	17,950	385.55	391.03	389.92				
	Chalerm Prakiat Bridge (Kok26)	18,700	384.40	390.11	390.17				
	Nam Korn confluence (Kok28)	19,700	382.40	390.00	389.30				
	Chiang Rai Weir (Kok30)	21,700	380.52	388.39	389.95	4.00	11 x 8.00	385.75	11 radial gates
	Nam Mae Lao confluence (Kok31)	22,700	375.25	388.77	389.95				
	Ban Mae Phaeng (Kok60)	54,200	368.72	375.35	374.69				
	Kok mouth at Sop Kok (Kok88)	90,650	354.18	364.86	360.32				
Lao	Ban Pong Pu Fuang (LAO-145)	0,000	438.74	442.44	442.83				
	Mae Lao Weir (LAO-120)	12,450	428.24	430.96	431.18	3.50	35.50	431.00	Ungated
	Tham Wok Weir (LAO-84)	28,950	412.02	415.24	414.76	2.10	60.00	413.15	Ungated
	G8-Ban Ton Yang (LAO-71-70)	35,060	404.92	408.80	409.25				
	Ban Rim Lao (LAO-55)	42,810	400.42	403.28	403.54				
	Ban Tha Sai (LAO-35-34)	53,060	395.15	399.72	399.67				
	Chai Sombat Weir (LAO-28)	55,810	392.29	398.15	396.74	2.70	50.00	395.87	Ungated
	Lao mouth d/s CR Weir (LAO-0)	69,010	375.30	386.34	386.49				
Korn	U/S boundary W4 Weir (Kn 23.0)	0,000	407.85	411.85	412.35	2.10	3 x 2.40	408.75	Gated: 3 gates
	W3 Weir (Kn21.5)	1,450	405.31	408.06	408.11	2.10	3 x 2.40	407.41	Gated: 3 gates
	W2 Weir (Kn18.0)	4,950	400.66	403.10	403.12	2.10	3 x 2.40	402.76	Gated: 3 gates
	W1 Weir Canal Offtake (Kn17.0)	5,950	397.54	402.09	401.72	1.50	9 x 1.50	397.49	Gated: 9 gates
	C.R.M. Weir (KORN 41-M)	17,676	388.30	390.20	390.30	2.00	15.50	393.30	Ungated
	Korn mouth (Kn00.0)	22,410	382.42	389.53	389.18				
Korn-Kok Canal	Canal intake (KK1)	0,000	397.54	400.79	400.79	2.50	4 x 2.50	397.24	Gated: 4 gates
	Canal outlet (KK25)	4,210	390.46	396.14	396.14	2.50	4 x 2.50	392.91	Gated: 4 gates

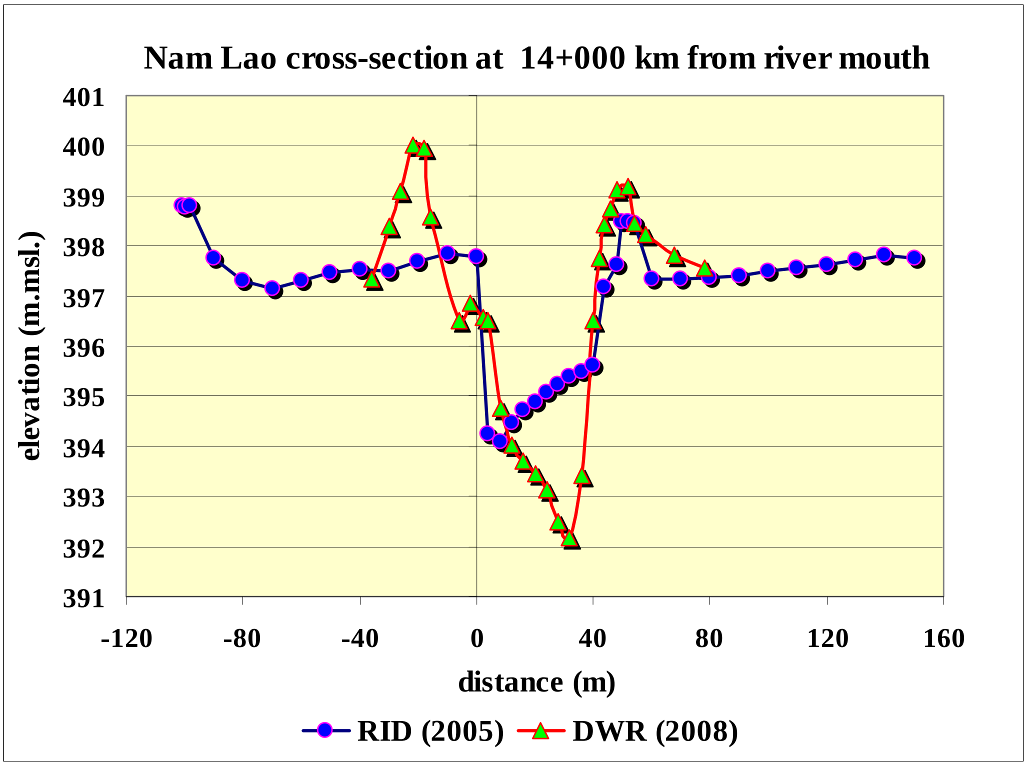

Figure 5-1 Cross-sections of Nam Mae Lao before and after implementation of river embankments.

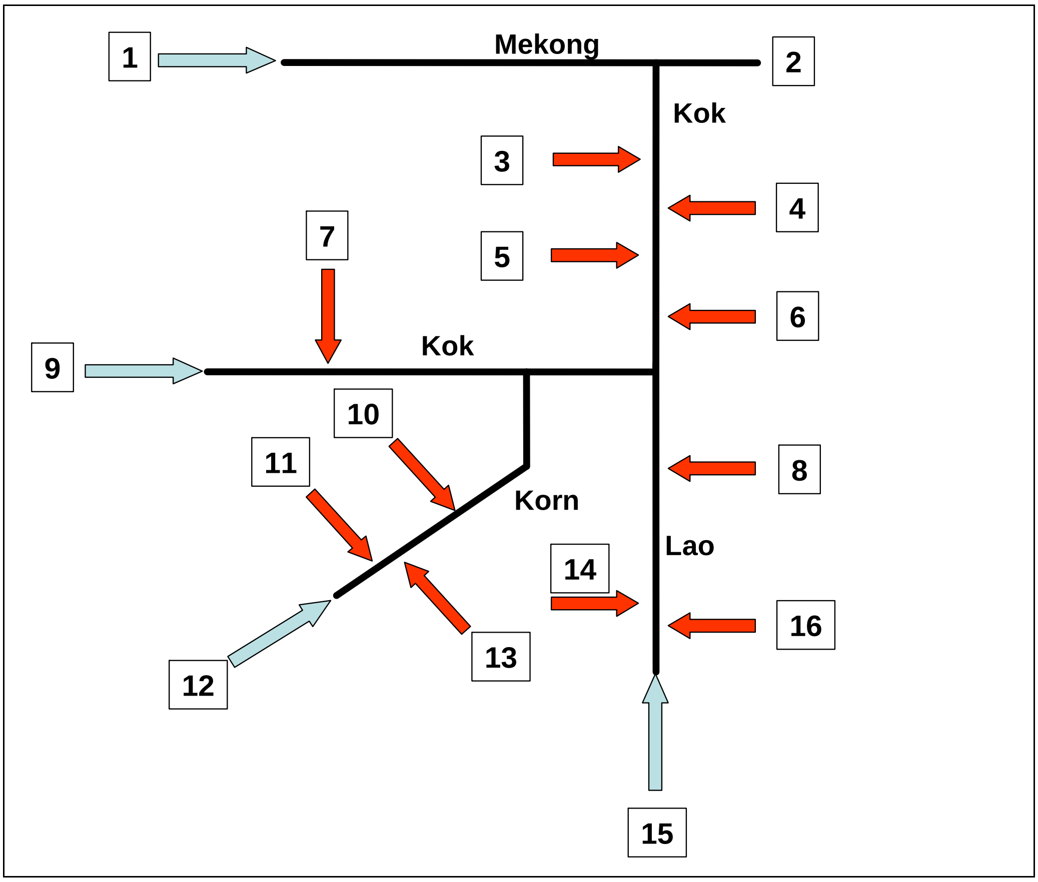

Figure 5-2 Schematic view of the required boundary conditions for running of hydraulic model. The numbers are described in Table 5-2.

Table 5-2 Description of the boundary nodes of the hydraulic model (see Figure 5-2).

no	Description
1	Inflow from the Mekong River at Chiang Saen Hydro Station
2	Water Level of the Mekong at Sop Kok Station
3	Lateral flow to the Nam Kok from SWAT subbasin 3 at cross section no. 70 to 79
4	Lateral flow to the Nam Kok from SWAT subbasin 15 at cross section no. 45
5	Lateral flow to the Nam Kok from SWAT subbasin 16 at cross section no. 40 to 4
6	Lateral flow to the Nam Kok from SWAT subbasin 8 at cross section no. 44
7	Lateral flow from SWAT subbasin 7 to the Nam Kok at cross sections downstream
8	Lateral flow to Nam Lao from SWAT subbasin 9 at the Lower Nam Lao
9	Upstream boundary condition for the Nam Kok at Ban Pong Na Kham (030102)
10	Lateral flow from SWAT subbasin 7 contributing to the Lower Nam Korn
11	Runoff from SWAT subbasin10 area downstream of cross section Kn23.0
12	Upstream boundary condition for the Nam Korn
13	Balance node, not relevant here
14	Lateral flow to the Nam Lao from SWAT subbasin 10 at downstream cross sections
15	Upstream boundary condition for the Nam Lao at Ban Pong Pu Fuang (030302)
16	Lateral flow to the Nam Lao from SWAT subbasin 11 at downstream cross sections

Calibration and validation

The calibration for the pre-2005 conditions was carried out by Kittipong (2009) for the years 2000-2004, looking particularly at a proper reproduction of the peak values. It appears that the peaks are generally reasonably matched. However, the recession curve is highly overestimated by the model, which is a direct consequence of the overestimation of the lateral inflow. It can be said that due to the overestimated lateral inflow the hydraulic roughness will be underestimated. When the lateral inflows are brought to a realistic level a recalibration of the model will be required.

The model has subsequently been validated implementing the developments in the hydraulic infrastructure since 2005, including the bypass canal from Korn to Kok, rehabilitated weirs in the Korn and raising of the embankments along the Lao from 15 km u/s Chai Sombat Weir to the Chiang Rai Weir. Comparison of the cross-sections in the model prior to and from 2005 onward revealed that the newly surveyed cross-sections were not included in the model as such, but lead only to raise weir sills in the connection between river and floodplain. As can be seen from Figure 5-1, the river cross-section also contains a floodplain. By raising the weir sill, this floodplain is left unchanged and only the floodplain away from the river cross-section is affected. Due to this approach the capacity of the river with its direct floodplain is overestimated (by the measure it is eliminated but by the way of schematisation it is left intact). This erroneous schematisation requires a larger hydraulic roughness to match the observed water levels.

In summary: the hydraulic model of the Kok River and floodplain will not be suitable for flood mapping unless a recalibration takes place based on improved lateral inflows and corrected schematisation of the flood mitigation measures since 2005.

5.3 Selection of model boundary conditions

5.3.1 Introduction

Figure 5-2 of section 5.2 showed all boundary nodes of the hydraulic model. In the flood hazard analysis the model is run for various hydraulic scenarios. For each scenario there are 16 boundary conditions. Chapter 4 describes the statistics of river discharges on which these scenarios and boundary conditions should be based. Below we describe the step-by-step procedure of how the input series for the scenarios are composed. As explained in section 5.1, the analysis is executed for different areas in the Kok Basin, each area having its own unique set of representative boundary conditions.

5.3.2 Area 1a: Nam Mae Kok upstream of Lao confluence

For this area 90 different scenarios are simulated, which are combinations of:

- 6 values of the peak discharge of the Nam Mae Kok at Ban Pong Na Kham;
- 5 associated flow volumes of the Nam Mae Kok at Ban Pong Na Kham;
- 3 associated flow volumes of the Nam Mae Korn and the Nam Mae Lao.

The 90 scenario’s synthetic hydrographs are first derived for the Kok and Lao rivers using the following procedure:

1. Select peak discharges of the Nam Mae Kok (at Ban Pong Na Kham) with return periods 2, 5, 10, 25, 50 and 100 years from Table 4-1.
2. Select associated flow volumes of the Nam Mae Kok using [a] the regression equation of Figure 4-3 and [b] deviations of -1.96, -1, 0, 1 and 1.96 times the standard deviation from the regression line (with the standard deviation being equal to 129 MCM).
3. Derive the ratio of volume/peak for all 6×5 combinations of peak discharge and flow volume. Then, for each combination, select a historically observed hydrograph with the same volume/peak ratio. Multiply this observed hydrograph by: (scenario peak/observed peak). The result is a hydrograph with the required peak and volume of the scenario. Note that instead of using 1 observed hydrograph, generally interpolation between two observed hydrographs is required to obtain the exact volume/peak ratio of the scenario.
4. For each of the 30 scenarios of step 1-3 select associated flow volumes of the Nam Mae Lao using [a] regression equation (4.1) and [b] deviations of -1.96, 0, 1.96 times the standard deviation from the regression line (with the standard deviation being equal to 70 MCM).
5. For each of the resulting 90 (6×5×3) flow volumes, construct a synthetic hydrograph for the Nam Mae Lao, which has exactly the derived volume of step 4. For this purpose an observed hydrograph is selected with a volume that is relatively close to the desired volume. Subsequently, the hydrograph is rescaled in such a way that it has exactly the desired flow volume.

The resulting hydrographs for the Kok and Lao form the basis of the series of other lateral inflows and upper boundary flows, i.e. the inflow of other nodes are simply determined from these two hydrographs through application of multiplication factors. First, from the analysis of chapter 4, the following 7 series can be determined:

[a] Nam Mae Kok at Ban Pong Na Kham (see above);
[b] Nam Mae Lao at Ban Pong Pu Fuang (see above);

[c] Nam Mae Korn at upstream boundary: 0.16*series [b];
[d] Lateral inflow of the Nam Mae Korn: 0.42*series [c];
[e] Lateral flow for the Nam Mae Lao between Ban Pon Pu Fang and Kok-Lao confluence (Chiang Rai Weir): 0.029*series [b];
[f] Lateral inflow between Lao-Korn confluence and Ban Mae Phang: 0.113*(sum of series [1] till [4]);
[g] Lateral inflow between Ban Mae Phang and Mekong: 0.027*(sum of series [1] till [4]).

From the above series, input for 13 of the 16 boundary nodes of Figure 5-2 is derived (see Table 5-3). The only exceptions are nodes 1, 2 and 13. Node 13 is a dummy node and therefore not of interest here. Nodes 1 and 2 are the boundary conditions on the Mekong River. For the area under consideration (area 1a, Nam Mae Kok upstream of Lao confluence) the flow in the Mekong River has no influence on the water levels. Therefore, a more or less arbitrary discharge of 10,000 m^3/s is assumed in node 1, resulting in a water level of MSL+363.35 m in node 2 (Chiang Saen). See Table 5-3.

Table 5-3 Input series for model boundary nodes

no	Input series
1	constant discharge of 10,000 m^3/s
2	constant water level of MSL+363.35 m
3	series [g]
4	series [f] / 3
5	series [f] / 3
6	series [f] / 3
7	series [d] / 3
8	series [e] / 3
9	series [a]
10	series [d] / 3
11	series [d] / 3
12	series [c]
14	series [e] / 3
15	series [b]
16	series [e] / 3

5.3.3 Area 1b: Nam Mae Lao upstream of Kok confluence

The procedure for area 1b is very similar to the procedure of area 1a in the previous section. Again, 90 different scenarios are simulated, which are combinations of:

- 6 values of the peak discharge of the Nam Mae Lao at Ban Pong Pu Fuang;
- 5 associated flow volumes of the Nam Mae Lao at Ban Pong Pu Fuang;
- 3 associated flow volumes of the Nam Mae Korn and the Nam Mae Kok.

The 90 scenario’s synthetic hydrographs are first derived for the Lao and Kok rivers using the following procedure:

1. Select peak discharges of the Nam Mae Lao (at Ban Pong Pu Fuang) with return periods 2, 5, 10, 25, 50 and 100 years from Table 4-1.
2. Select associated flow volumes of the Nam Mae Lao using [a] the regression equation of Figure 4-12 and [b] deviations of -1.96, -1, 0, 1 and 1.96 times the standard deviation from the regression line (with the standard deviation being equal to 54 MCM).
3. Derive the ratio of volume/peak for all 6×5 combinations of peak discharge and flow volume. Then, for each combination, select a historically observed hydrograph with the same volume/peak ratio. Multiply this observed hydrograph by: (scenario peak/observed peak). The result is a hydrograph with the required peak and volume of the scenario. Note that instead of using 1 observed hydrograph, generally interpolation between two observed hydrographs is required to obtain the exact volume/peak ratio of the scenario.
4. For each of the 30 scenarios of step 1-3 select associated flow volumes of the Nam Mae Kok using [a] the regression equation of Figure 4-14) and [b] deviations of -1.96, 0, 1.96 times the standard deviation from the regression line (with the standard deviation being equal to 254 MCM).
5. For each of the resulting 90 (6×5×3) flow volumes, construct a synthetic hydrograph for the Nam Mae Kok, which has exactly the derived volume of step 4. For this purpose an observed hydrograph is selected with a volume that is relatively close to the desired volume. Subsequently, the hydrograph is rescaled in such a way that it has exactly the desired flow volume.

The resulting hydrographs for the Kok and Lao form the basis of the series of other lateral inflows and upper boundary flows, i.e. the inflow of other nodes are simply determined from these two hydrographs through application of multiplication factors. First, from the analysis of chapter 4, the following 7 series can be determined:

[a] Nam Mae Kok at Ban Pong Na Kham (see above);
[b] Nam Mae Lao at Ban Pong Pu Fuang (see above);
[c] Nam Mae Korn at upstream boundary: 0.16*series [b];
[d] Lateral inflow of the Nam Mae Korn: 0.42*series [c];
[e] Lateral flow for the Nam Mae Lao between Ban Pon Pu Fang and Kok-Lao confluence (Chiang Rai weir): 0.029*series [b];
[f] Lateral inflow between Lao-Korn confluence and Ban Mae Phang: 0.113*(sum of series [1] till [4]);
[g] Lateral inflow between Ban Mae Phang and Mekong: 0.027*(sum of series [1] till [4]).

From the above series, inputs for 13 of the 16 boundary nodes of Figure 5-2 are derived (see Table 5-3). The only exceptions are nodes 1, 2 and 13. Node 13 is a dummy node and therefore not of interest here. Nodes 1 and 2 are the boundary conditions on the Mekong River. For the area under consideration (area 1a, Nam Mae Kok upstream of Lao confluence) the flow in the Mekong River has no influence on the water levels. Therefore, a more or less arbitrary discharge of 10,000 m^3/s is assumed in node 1, resulting in a water level of MSL+363.35 m in node 2 (Chiang Saen).

CHAPTER 6

REFERENCES

6 REFERENCES

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PART B

FLOOD DAMAGE ASSESSMENT

FLOOD RISK ASSESSMENT

SOCIAL DIMENSIONS OF FLOODING

CHAPTER 1

FLOOD DAMAGE ASSESSMENT

1 FLOOD DAMAGE ASSESSMENT

In Chiang Rai Province flooding takes place near the city of Chiang Rai, located close to the confluence of the Nam Mae Kok and Nam Mae Lao. The city is flood prone when the rivers convey large discharges. The last major flood of 2006 came from the Nam Mae Lao and a small river named. The Nam Mae Lao drains downstream of Chiang Rai Weir, whereas the , draining an area immediately south of Chiang Rai, joins the Nam Mae Kok 2.9 km upstream of the Chiang Rai Weir. The latter two streams are interconnected by the Canal 14R-LMC. The canal joins the Nam Mae Lao at the Chai Sombat Weir, about 3 km downstream of the Highway Nr 1 Bridge across the river.

One of the measures for flood control implemented is a bypass canal from the Korn to the Kok west of Chiang Rai, d/s of the Korn-Lao connection. This bypass increases the discharge of the Nam Mae Kok in the city and it will only reduce the flow from the Korn to the Lao if the canal flow is fully controlled.

The surveys of flood damages at Mueang Chiang Rai District in Chiang Rai City and Chiang Saen District near the Kok River mouth were carried out.

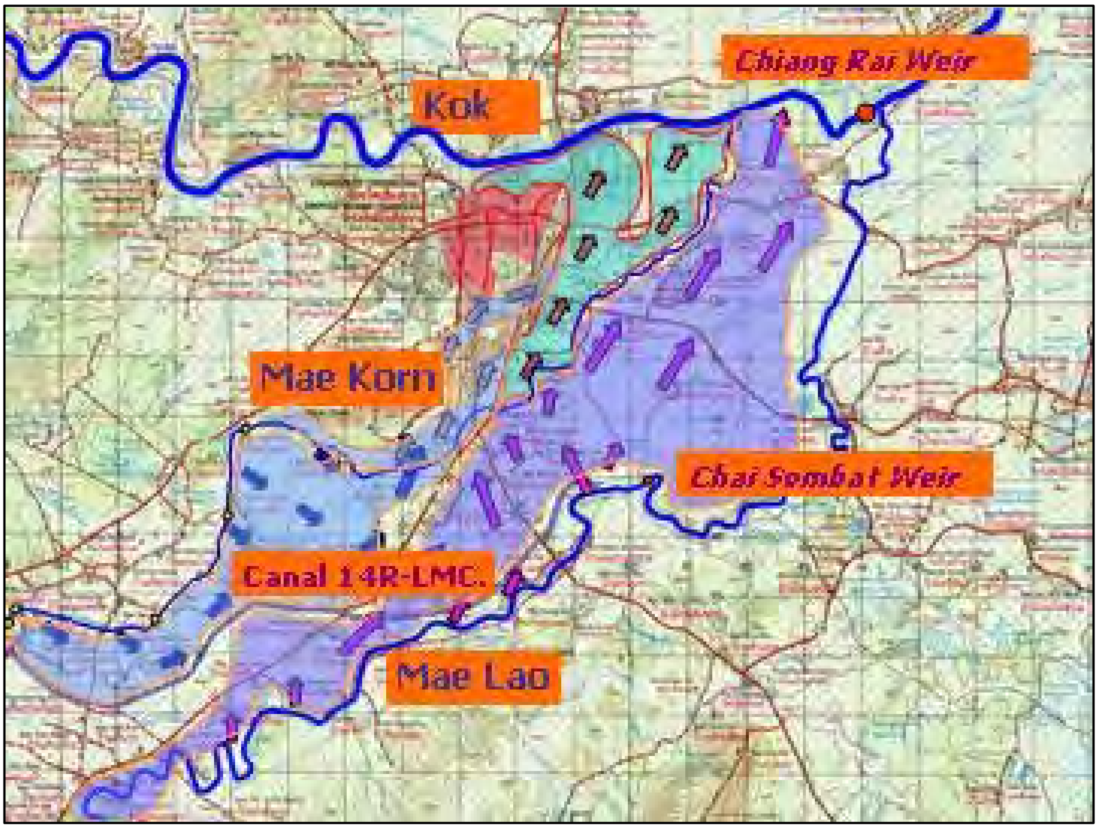

Figure 1-1 Map showing flooding in Chiang Rai near the city of Chiang Rai.

1.1 District Flood Damages Data

The direct damages caused by flooding in the two selected districts in the focal area were collected from district and provincial authorities for the period 2000-2008. During the first data collection in 2008, the survey team only collected the data from 2006-2008 with several items missing. The consultants went to Chiang Rai to visit related departments[2] in Chiang Rai province in March 2009 to see if additional flood damage data could be collected. The mission found out that there were more data available in related departments that the survey team had not been able to collect in 2008.

Additional data collection on direct flood was done and sent to the consultant in April 2009. The district direct flood damage inventory was for 6 years from 2003-2008. Most of damages were from agricultural production occupying 80-90% of the land in Mueang Chiang Rai District and 90-95% in Chiang Saen District. The infrastructure affected by flood is only rural roads and bridges. No flood damages for public infrastructure and utilities have occurred for education, health, irrigation, power & water supply, post & telecommunication, government office & market. See Table 1-1 and details are in Appendix 1.

Table 1-1 Direct flood damages 2003-2008 (1,000 USD).

Items	2003	2004	2005	2006	2007	2008
Chiang Rai	**1,425**	**2,614**	**806**	**232**	**247**	**55**
Housing	56	131	41	4	11	3
Agriculture	1,287	2,309	714	207	233	45
Infrastructure	83	174	51	22	3	7
Chiang Saen	**781**	**1,065**	**909**	**2,323**	**1,019**	**1,986**
Housing	8	19	33	78	26	74
Agriculture	735	990	851	2,208	968	1,872
Infrastructure	39	56	24	37	24	40

Direct Flood damage inventory, Thailand

The indirect damages for Housing are derived from the Household and Business surveys. It includes cost for relocation, re-establishment and temporary flood protection. The household survey showed that there were 96 out of 224 households under the survey suffered from the 2006 flood damages to their houses at different scale. Overall average damages by 2006 to houses were 520 USD/HH in Mueang Chiang Rai and 409 USD/HH in Chiang Saen District.

In the business survey there were 13 out of 34 businesses reported that their properties damaged by the 2006 flood. The overall average damages by 2006 were 1,045 USD per business in Mueang Chiang Rai District and 136 USD per business in Chiang Saen District.

The rate of indirect damages is 14.4% for household and 40% for business in Mueang Chiang Rai District. These rates are 3.4% for household and 15.9% for business in Chiang Saen District. The number of business were not available, therefore the weighted average for household and business was numerically calculated at 27% for Mueang Chiang Rai and 10% for Chiang Saen District. Overall indirect-direct ratio applied for the focal areas in Chiang Rai Province would be 20%. Details are presented in Table 1-2.

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[2] Regional/Provincial Disaster Prevention & Mitigation, Royal Irrigation Department, Regional/Provincial Rural Road Development, Town Planning Office, Provincial Statistic Office, Agricultural Extension Services, Chiang Rai Fishery Department.

Table 1-2 Direct and indirect damages for households and businesses (2006, USD).

Items	Unit	Chiang Rai	Chiang Saen
Direct damages HH	USD	69,709	36,849
Indirect damages HH	USD	9,814	1,251
HH in Survey	HH	134	90
HH in District	HH	18,870	10,685
HH Survey Coverage	%	0.7	0.8
Weighted Indirect/Direct HH damages	%	14.1	3.4
Direct damages Businesses	USD	13,580	2,851
Indirect damages Businesses	USD	5,431	454
Businesses in Survey	Business	13	21
Businesses in District	Business	n/a	n/a
Business Survey Coverage	%	n/a	n/a
Average Indirect/Direct Bus. damages	%	40.0	15.9
Weighted Indirect/Direct HH & Business damages	%	27	10

Household and business survey, Thailand

Indirect damages for Infrastructure & Relief for 2006 were collected from relevant departments in the two selected districts. In Mueang Chiang Rai District, the total indirect costs in 2006 were USD 118,086 according to the Transportation Department. Other departments reported no indirect costs related to the 2006 flood. Direct flood damage in 2006 for Infrastructure & Relief was USD 118,086. The indirect/direct rate was estimated at about 8%. See Table 1-3. It seems to be under estimation of direct costs since data was not available for the team during the survey. There is no information on direct and indirect damages in 2006 in Chiang Saen District. This indirect-direct rate was used to adjust the direct damages reported by local government for the years 2006-2008.

To make the damage data of the various years comparable with each other and with data of other MRC Member Countries, the data have been converted to the 2007 price level[3] and have been converted to USD. The general CPIs were 102%, 107.6%, 113%, 117%, and 122.4% for 2003-2007 respectively.

Table 1-3 Direct and indirect damages for infrastructure 2006 (USD).

Items	Chiang Rai	Chiang Saen
Direct costs	1,514,286	n/a
Indirect costs Government	118,086	n/a
Indirect/Direct damages	7.8%	-

Floods along the Nam Mae Fang and In Chiang Rai province are classified as tributary flood. High flood water level is normally in August-September. The major rice is in August-December and corn is in July-December, both falling in the main flood season, therefore maximum flood water level would be selected as the key factor in damage function for crops, housing and infrastructure.

There are two key control hydrological stations in the focal area: (i) Chiang Rai station, which is located down stream of the Chiang Rai City with 26 years data available from 1978-2005. The flood water level of the station would be used for flood damage assessment for Mueang Chiang Rai District; and (ii) Chiang Saen station on the Mekong River with 47 years data available 1961-

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[3] Using CPI reported by Chiang Rai Statistic Office, period 2003-2007

2007. The flood water level of Chiang Saen station would be used for flood damage assessment for Chiang Saen District.

In Chiang Saen District, flood damage for infrastructure in 2003 and 2004 was out of the range of the relationship (high flood damage at low water level). It may be the damage in these years included the investment of rural road/bridges for the following years. It needs further investigation on these matters. See Table 1-4.

Table 1-4 Flood direct and indirect damages (1,000 USD), at 2007 fixed price.

Year	Total	Housing	Agriculture	Infrastructure	Max WL
Mueang Chiang Rai District					
2003	1,732	80.2	1,544.1	107.3	4.31
2004	3,019	178.4	2,626.4	214.1	4.57
2005	887	53.0	773.9	59.8	4.29
2006	245	4.5	216.0	24.7	NA
2007	250	13.2	233.0	3.7	NA
2008	54	3.7	43.3	7.0	NA
Chiang Saen District					
2003	943	11.6	881.5	50.0	6.79
2004	1,220	25.4	1,126.4	68.6	8.40
2005	993	43.1	922.3	28.0	8.59
2006	2,450	97.8	2,309.5	42.3	9.71
2007	1,026	31.6	968.3	25.9	8.15
2008	1,940	86.0	1,812.3	41.9	NA

District flood damage inventory, Thailand and consultant estimates

1.2 Damage and Probability for Districts

As evaluated in Part A: Flood Hazard, the mathematical hydraulic model of the Nam Mae Kok and Nam Mae Lao was developed by DWR/TNMC in 2006 for the case study:" Flood/drought for Kok River Basin". However, the quality of the model was considered to be insufficient for reliable flood hazard assessment in the Chiang Rai region. So no hydraulic model simulations were available for translation of hydrological hazard into flood hazard as flooding depth and duration. Therefore, flood damage assessment for the focal area could only be done by the Absolute Approach Methodology[4].

Absolute flood damage curves for infrastructure, housing, and agriculture were established for the two districts in the Nam Mae Kok Focal Area. See Figure 1-1 and Figure 1-3.

Damage probability curve for the districts was developed by historical flood water levels recorded at Chiang Rai and Chiang Saen stations in a combination with absolute flood damage curves. See Figure 1-4 and Figure 1-5.

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[4] See The Best Practice Guidelines for Flood Risk Assessment, FMMP-C2

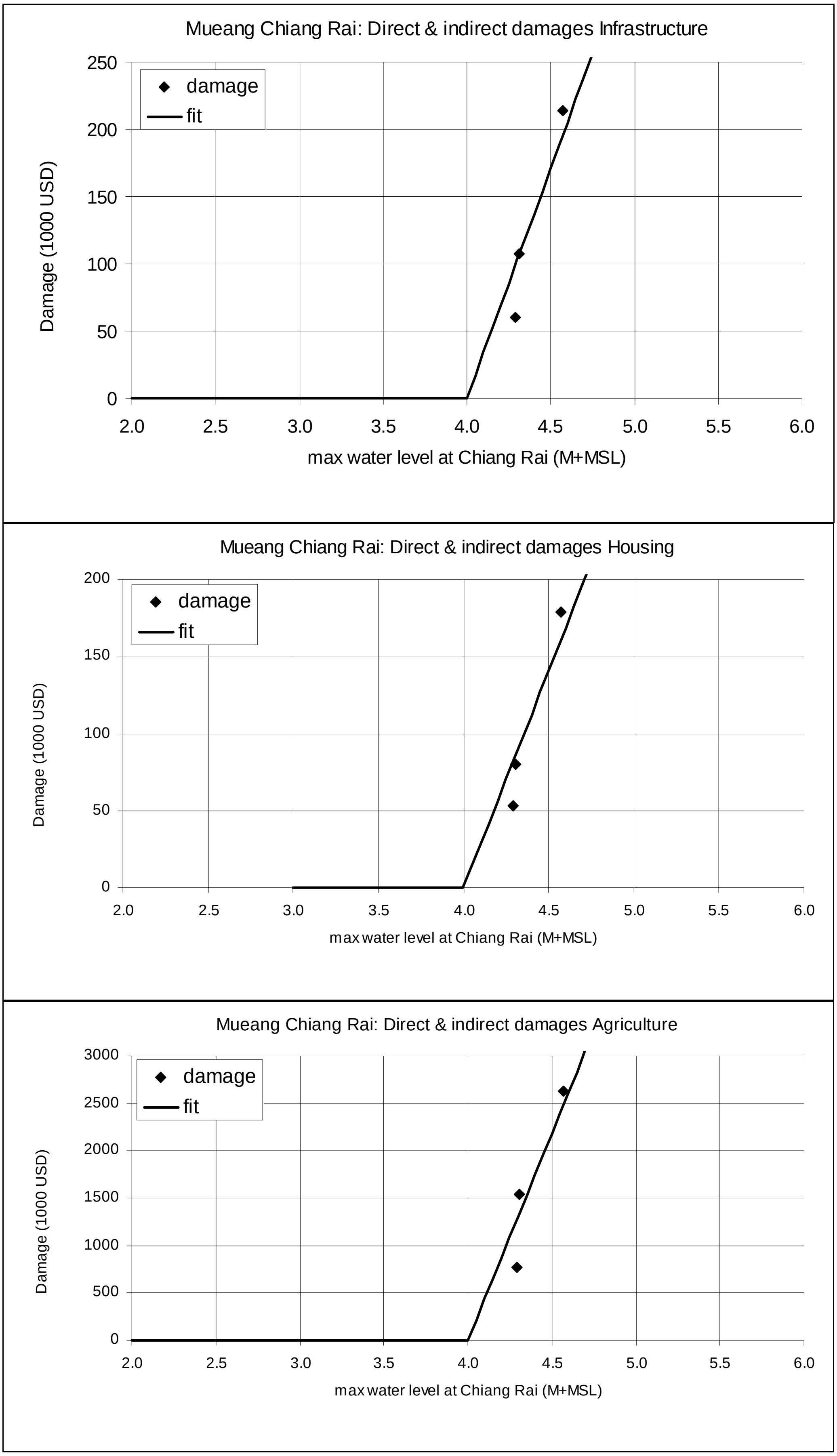


Figure 1-2 Absolute Damage Curves for Mueang Chiang Rai District.

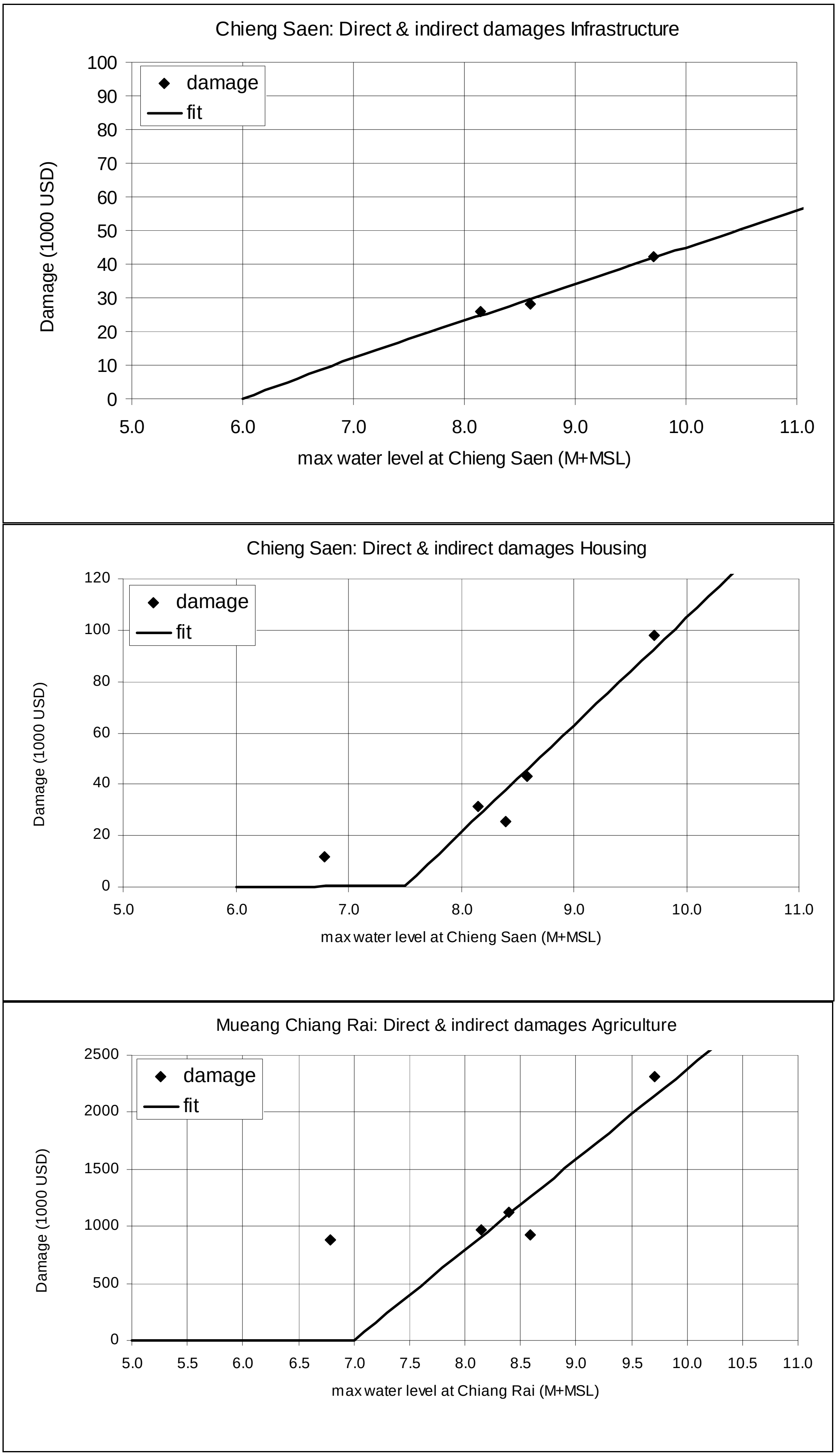


Figure 1-3 Absolute Damage Curves for Chiang Saen District.

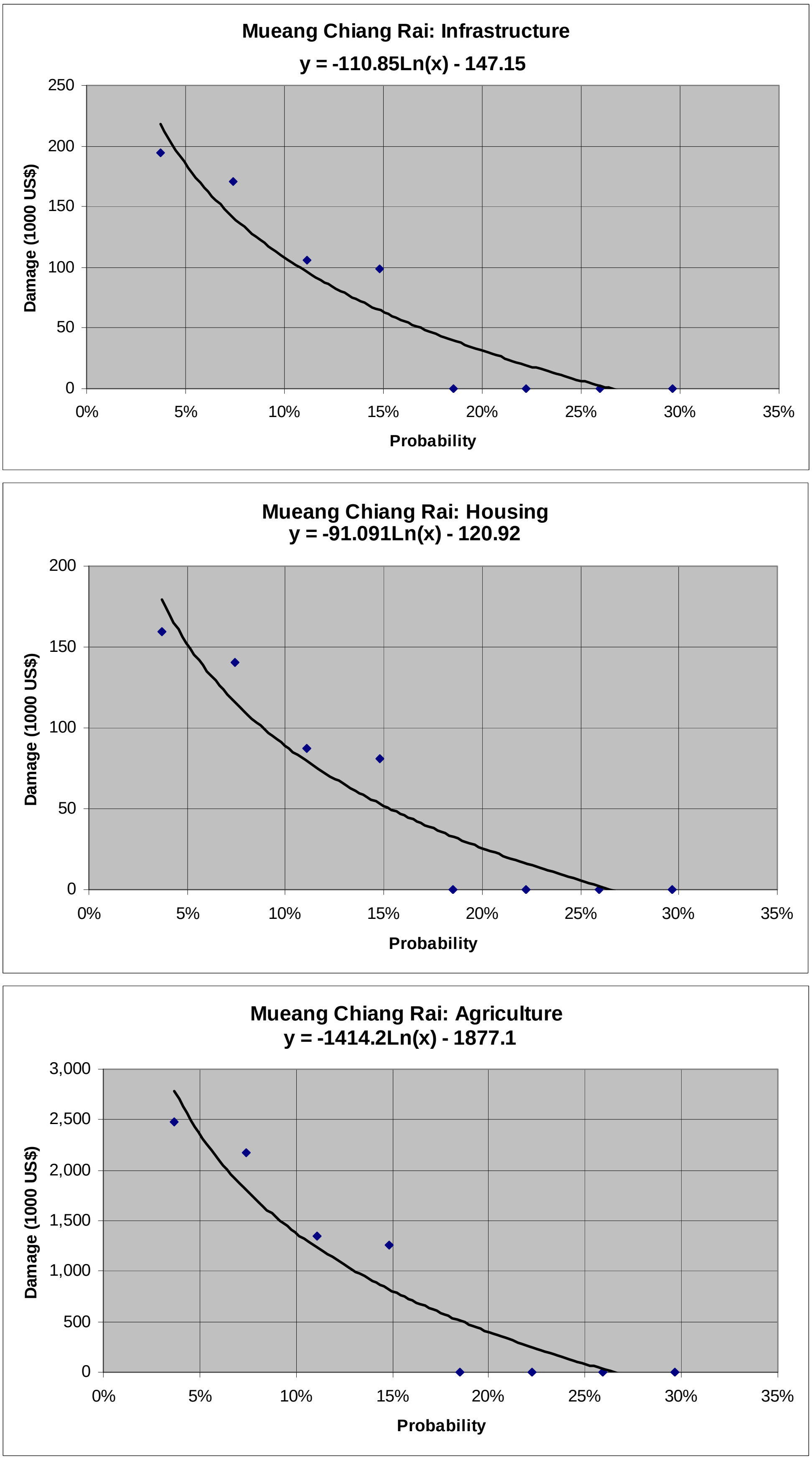
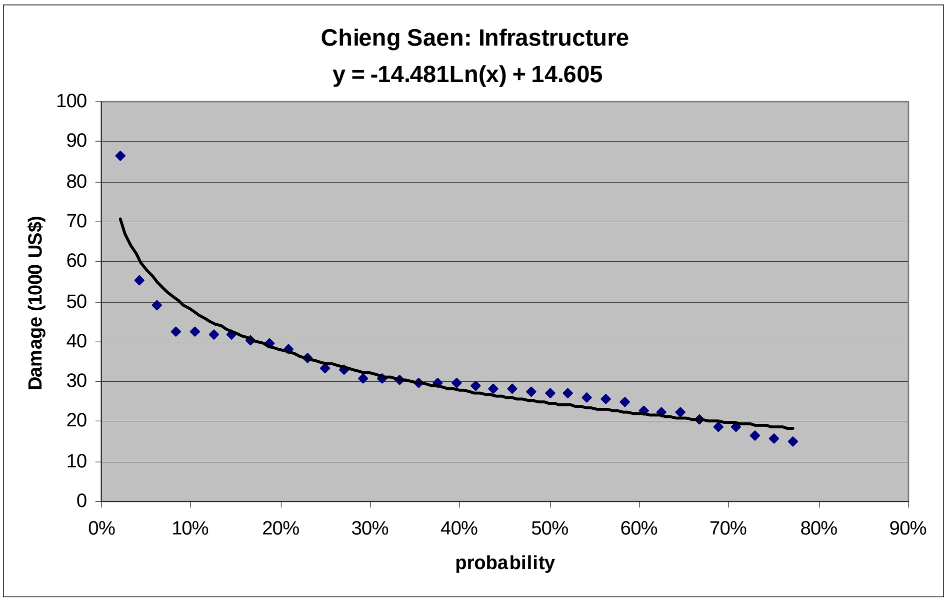
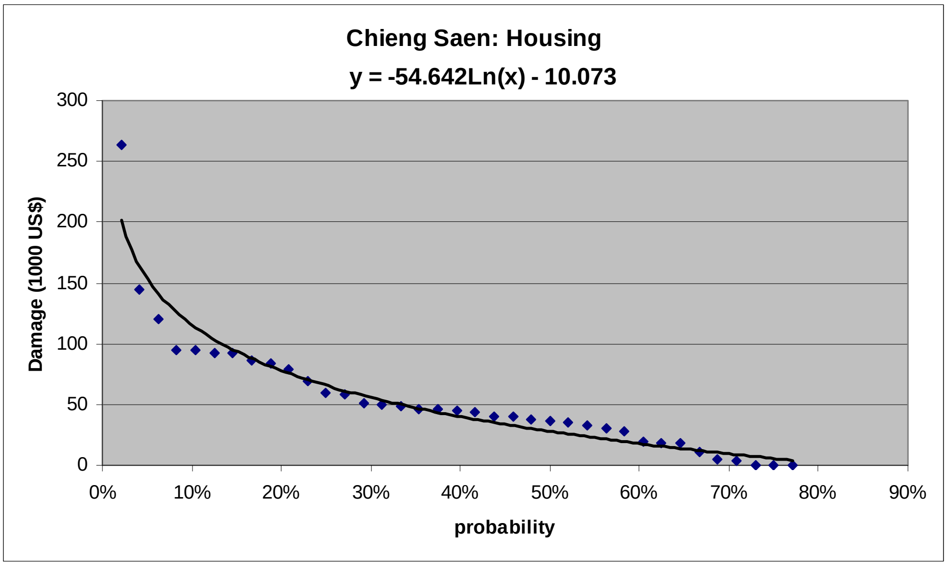


Figure 1-4 Damage probability curves for Mueang Chiang Rai District.





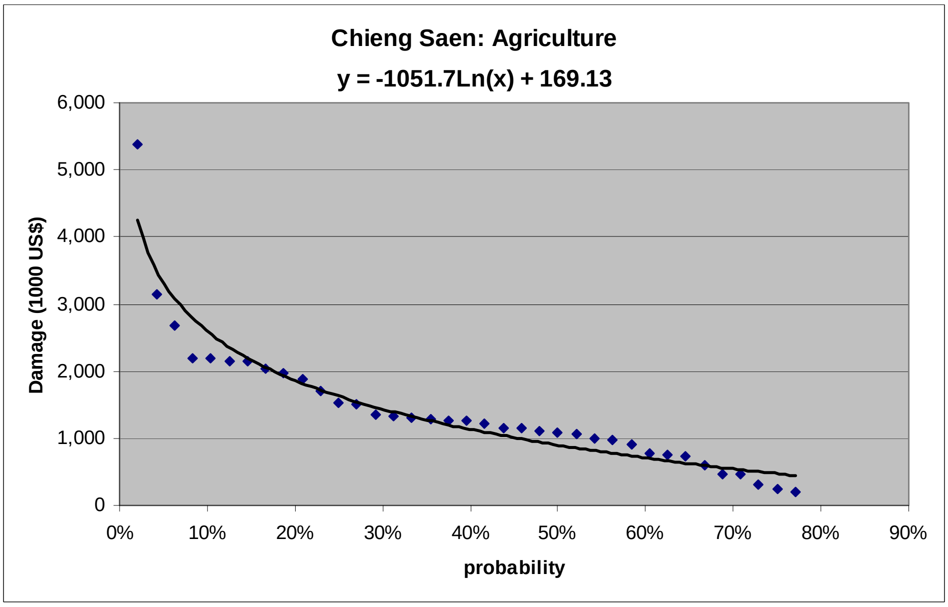


Figure 1-5 Damage probability curve for Chiang Saen District.

1.3 District Population, Land Use and Structure

According to the District statistics, the population in 2006 was about 77,000 people in Mueang Chiang Rai District and about 54,000 people in Chiang Saen District. The average annual population growth rate during the period of 2001-2006 was 1.76% in Mueang Chiang Rai and 1.9% in Chiang Saen.

In Mueang Chiang Rai District, land use in 2006 was as agricultural land including plantation of 45% and forest land of 45%, the remaining are residential and infrastructure.

In Chiang Saen District, land use in 2006 was as agricultural land including plantation of 41% and forest land of 54%, the remains are residential and infrastructure.

Table 1-5 Population and land-use in selected districts, 2006.

Items	Unit	Mueang Chiang Rai	Chiang Saen
Population			
Population	Person	76,818	53,537
Number of HH	HH	18,870.00	10,685
Size of Family	Person	4.07	5.01
Poor household	HH	n/a	n/a
Population growth rate (2001-2006)	%	1.76%	1.90%
Land Use			
Rice Land – Irrigated	Ha	4,907	-
Rice Land - Not irrigated or rain-fed	Ha	41,309	11,594
Crop Land	Ha	28,004	9,772
Plantation Land	Ha	19,892	24,782
Residential - Rural (including gardens)	Ha	6,526	1,537
Residential – Urban	Ha	6,643	265
Commercial/Industrial	Ha	466	7
Institution	Ha	1,662	24
Forest	Ha	93,256	60,911
Communal land	Ha	4,801	4,849

District flood vulnerability & flood event, Thailand

There is no information on type of house in the district statistics provided to the survey team. However, from field observation it is noted that most houses are in permanent and semi-permanent.

Agricultural land is mainly used for paddy cultivation in Mueang Chiang Rai. There was a small upland crop area for corn, pineapple, Vegetables, cassava and longan fruit tree. The land use for upland crops in Chiang Saen District has higher percentage than that in the Mueang Chiang Rai District. See details in Table 1-6.

Table 1-6 Crops in selected districts, 2006.

Items	Unit	Mueang Chiang Rai	Chiang Saen
Rice	ha	2,545	11,594
Upland crops	ha		11,892
Plantations	ha		577
Corn	ha	605	
Pine apple	ha	172	
Vegetables	ha	226	415
Cassava	ha	226	
Mango fruit tree	ha	14	
Longan fruit tree	ha	258	

District flood vulnerability & flood event, Thailand

1.4 Household and Business Survey

The survey sample was 147 households and business in Mueang Chiang Rai and 111 households and businesses in Chiang Saen District in the focal area. The survey showed that 58% of respondents reporting that their house and/or business damaged by the 2006 flood.

The average value of the houses varies from 11,000 to 16,000 USD with an area varying from 80 to 120 m^2. Average value of business structure varies from 9,000 to 43,000 USD with an area varying from 250 to 4600 m^2.

The damages to houses in 2006 were 3-6% of the house value for Households and 1-3% for Business. The hypothetic investigation on potential flood damages if flood level being higher than the 2006 level was tested. The graph below presents the relative damages curves for house and business structure in the two selected districts. See Figure 1-5 and Figure 1-6.

1.5 Damage curves for paddy cultivation

Based on information collected during the Focal Group Discussions (FGD), the main paddy crop is planted during May-June and harvested during November-December. The crop cycle falls in flood season. Floods would cause damage to rice crops in a period of Mid of September – Mid of October for a normal flood year; and in a period of Mid of August – Mid of October for a big flood year.

High flood flow in the area often occurs during August-September which is almost at the middle of the crop cycle. The damage to paddy depends on (i) depth of flood water; and (ii) duration of flood. The household survey on 2006 flood events and damages to crops in the two selected districts showed that:

1. The rice crop suffers from flood damages when flood duration last more than 5 days;
2. In most of the cases, when flood depth of 1.5m or more and flooding duration of more than 13 days, the damages to rice was estimated as 100%;
3. Potential paddy yield in household survey for the two representative districts was 0.9 ton/rai equivalent to 5.6 ton/ha. The maximum total production losses would be 1,285 USD/ha;
4. It is assumed that depth of flooding of 0.5 m would not affect the paddy. At flooding depth of 1.5 m or more 100%, 85%, 65%, and 40% damage if flood duration of more than 13 days, 11 days, 9 days and 7 days respectively.

Table 1-7 Household & Business survey in the selected districts.

Items	**Unit**	**Mueang Chiang Rai**		**Chiang Saen**	
		Household	**Business**	**Household**	**Business**
Total sample	**HH**	**134**	**13**	**90**	**21**
Permanent house	HH	123	9	84	19
Semi-permanent	HH	10	4	6	1
Temporary	HH	1	0	-	1
Houses affected by 2006	**HH**	**66**	**9**	**71**	**4**
Value of house	**USD**	**16,497**	**43,077**	**11,216**	**8,592**
Permanent house	USD	16,878	60,000	11,460	9,316
Semi-permanent	USD	11,886	5,000	7,810	571
Temporary	USD	15,714		-	2,857
Housing area	**m^2**	**117**	**4,563**	**81**	**251**
Permanent house	m^2	116	5,845	81	272
Semi-permanent	m^2	121	1,678	82	36
Temporary	m^2	160	-	-	60
2006 flood depth in garden					
Maximum	m	3.0	2.0	3.0	1.5
Overall	m	1.0	1.5	1.3	0.9
2006 flood depth on field					
Maximum	m	3.3	-	5.0	-
Overall	m	1.2	-	2.6	-
2006 flood depth in house	**m**	**0.5**	**0.8**	**1.1**	**0.7**
Damages to housing					
2006 flood	%	3.4	2.4	5.4	1.6
2006 flood +0.5m	%	4.0	4.9	6.5	8.8
2006 flood +1.0m	%	5.1	7.9	7.7	18.5
2006 flood +1.5m	%	10.1	13.8	11.2	32.3
2006 flood +2.0m	%	17.8	30.1	17.8	40.3

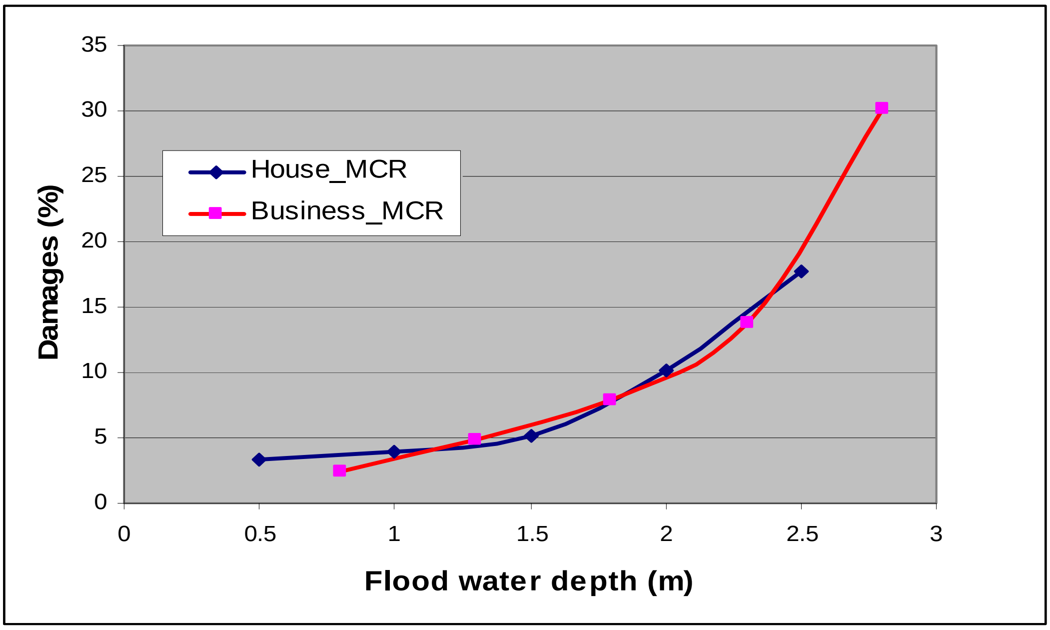


Figure 1-6 District relative flood damage curve for housing in Mueang Chiang Rai.

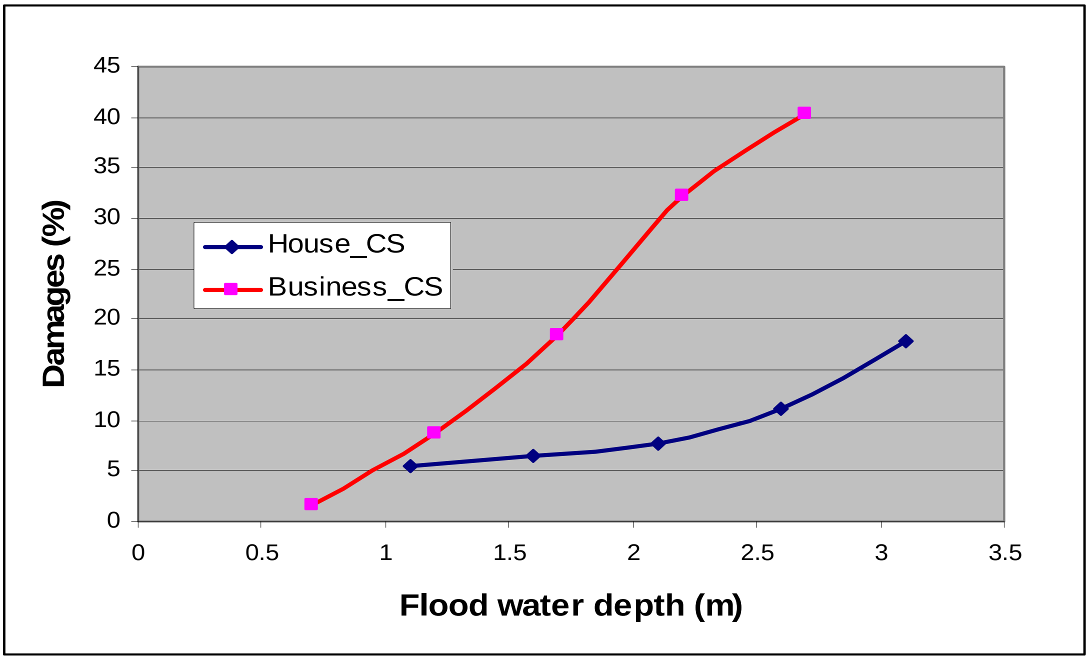


Figure 1-7 District relative flood damage curve for housing in Chiang Saen.

There are two relative damage curves for paddy prepared for flexibility in using it depending on application. The first curve shows relationship between depths of flooding, flooding duration with paddy damage in terms of percentage of total production. The second curve shows the relationship between depths of flooding, flooding duration with paddy damage in terms of USD/ha affected. See Figure 1-8 and Figure 1-9.

The first damage curve would have a wider application than the second one. Since the second one is for the area under the survey where paddy yield is about 5.6 ton/ha/crop.

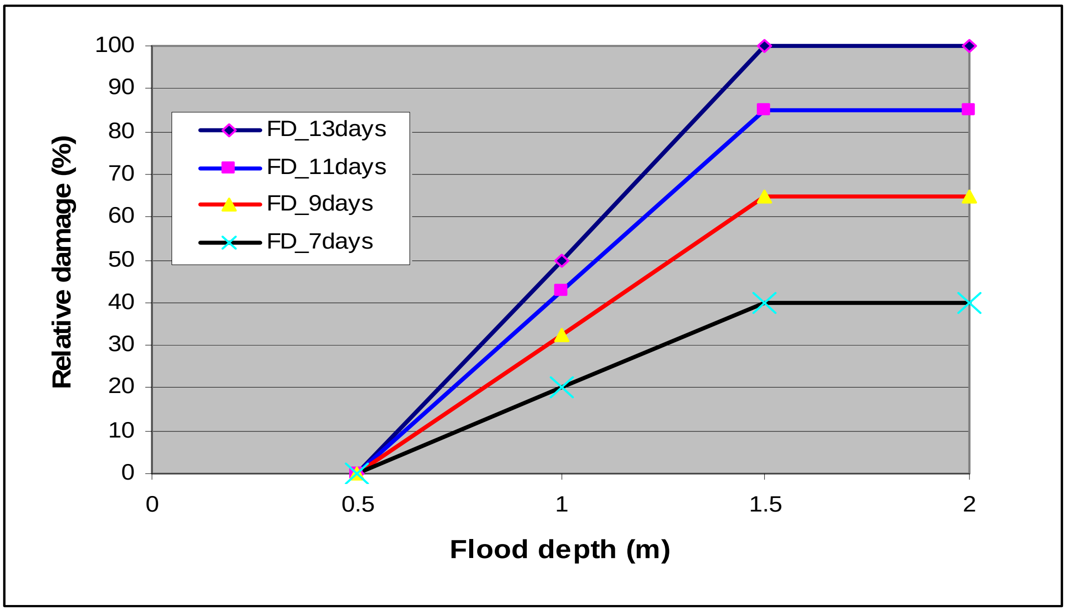


Figure 1-8 Relative damage curve for paddy in Nam Mae Kok Focal Area (%).

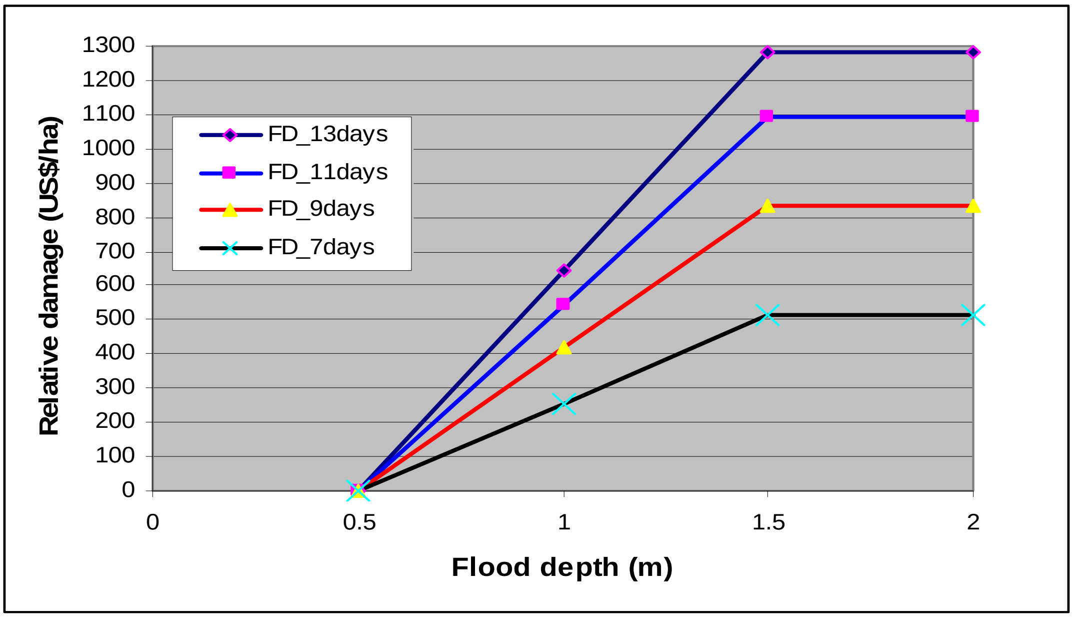


Figure 1-9 Relative damage curve for paddy in Nam Mae Kok Focal Area (USD/ha).

1.6 Benefit from Flooding

The summary of Focal Group Discussions with communities in Mueang Chiang Rai and Chiang Saen Districts show that there are benefits from the flooding to agriculture in terms of sedimentation and soil fertility to the land. In Ban Tha Sai sub-district, at normal situation, cost of fertilizer application is around 2,700 THB/ha. The cost of fertilizers application would be lower at around 2,500 THB/ha and the same for other inputs to keep the same crop yield. The net benefit from flooding for agriculture would be 200 THB/ha or equivalent to a value of 6 USD/ha.

The FGDs mentioned that many people are engaged in capture fisheries in the rivers and paddy fields and it is considered that natural fish in flood season is the main protein source for local people. No information is available on fish catch and/or approximated fish value.

CHAPTER 2

FLOOD RISK ASSESSMENT

2 FLOOD RISK ASSESSMENT

2.1 Limitation to flood risk assessment in the Nam Mae Kok Basin

Flood damages have been assessed through a data collection and social surveys in 12 communes. Results show that damages have decreased considerably over the past years, likely as a result of the flood control measures that have been implemented in the area at Chiang Rai, but it is also possible that lower floods occurred in the past years. A proper risk assessment could not be established due to issues with the hydraulic model that makes it unsuitable for simulations at this point in time (see Part A).

Flood damage probability curves are presented but should be interpreted with great caution because these are indicative only, due to lack of hydraulic simulation results.

However, the methodologies applied to arrive at flood risk assessment are presented below and are based on the Best Practice Guidelines for Flood Risk Assessment (Volume 3A).

2.2 Mueang Chiang Rai District

The flood damages in Mueang Chiang Rai District are low, especially for housing and infrastructure. See Table 2-1.

The flood risk for housing, infrastructure, and agriculture respectively for various return periods are presented in Table 2-2; these result from the integration of the flood damage probability functions as estimated in Figure 1-4.

The flood risk at various return periods can also be used to express the potential damage reduction for flood control measures, for example measures provided at a level of a 50 year return period would result in risk reductions of 21, 18 and 274 thousands USD/year for the damage categories Infrastructure, Housing and Agriculture respectively.

Table 2-1 Potential flood damage for Mueang Chiang Rai District (1,000 USD).

T (year)	**100**	**50**	**25**	**10**	**5**	**2**
Probability	1%	2%	4%	10%	20%	50%
Infrastructure	363	286	210	108	31	0
Housing	299	235	172	89	26	0
Agriculture	4,636	3,655	2,675	1,379	399	0
TOTAL	5,297	4,177	3,057	1,576	456	0

Table 2-2 Flood risk for Mueang Chiang Rai (1,000 USD/year).

T (year)	**100**	**50**	**25**	**10**	**5**	**2**
Probability	1%	2%	4%	10%	20%	50%
Infrastructure	25	21	17	7	1	0
Housing	20	18	14	6	1	0
Agriculture	315	274	211	96	12	0
TOTAL	360	313	242	109	14	0

2.3 Chiang Saen District

Flood damages in Chiang Saen District are much higher than that in Mueang Chiang Rai District. Flood damages in the area are mainly in agriculture while the damages for housing and infrastructure are low. See Table 2-3.

The flood risk for housing, infrastructure, and agriculture respectively for various return periods are presented in Table 2-4; these result from the integration of the flood damage probability functions as estimated in Figure 1-5.

The flood risk at various return periods can also be used to express the potential damage reduction for flood control measures, for example measures provided at a level of a 50 year return period would result in risk reductions of 27, 40 and 1,114 thousand USD/year for the damage categories Infrastructure, Housing and Agriculture respectively.

Table 2-3 Potential flood damage for Chiang Saen District (1,000 USD).

T (year) **Probability**	**100** 1%	**50** 2%	**25** 4%	**10** 10%	**5** 20%	**2** 50%
Infrastructure	81	71	61	48	38	25
Housing	242	204	166	116	78	28
Agriculture	5,012	4,283	3,554	2,591	1,862	898
TOTAL	5,335	4,558	3,781	2,754	1,978	951

Table 2-4 Flood risk for Chiang Saen District (1,000 USD/year).

T (year) **Probability**	**100** 1%	**50** 2%	**25** 4%	**10** 10%	**5** 20%	**2** 50%
Infrastructure	28	27	26	23	19	10
Housing	42	40	37	28	19	4
Agriculture	1,160	1,114	1,037	857	638	246
TOTAL	1,231	1,181	1,099	908	676	260

2.4 Field observations on flood risk

The consultants visited the floodplain (from Chiang Rai City to the river mouth of Kok River in Chiang Saen District). The following observations were made:

1. Almost all houses are located on the side of the hill and/or are located on higher ground level, excepting temporary huts on cultivation fields for taking care of the crops. It is hard to see significant impacts of flooding to housing. The Chiang Rai City has already had flood protection measures to divert flood water from the Mae Lao to the Kok River by a diversion canal upstream of the city and by an embankment around the city;
2. The same situation holds for infrastructure and public utilities, where these have been located on higher ground, with the exception of some sections of rural roads at a low level still affected by flood;
3. Cropping system along the Kok River in a section near Chiang Rai City, where three gravity irrigation schemes exist, is mainly double rice. On the higher land mainly one rain-fed rice or upland crops is cultivated (corn, bean, soy-bean, and peanut). The mission stopped at the bridge on road 1098 crossing the Kok River midway from Chiang Rai City to the Kok River mouth. The area along the Kok River is as a narrow valley with

an elevation of 5-6m about water level in the dry season. The area is planted with upland crops (mainly corn). See photos.

- The main season corn is planted in April and harvested in June-July, normally before the flood comes;
- The second corn crop is planted in November and harvested in March-April with supplemental irrigation.

Farmers living in the area reported that the field would be submerged by big flood normally after the harvesting period at a depth of 1.5-3.0 m, except some early flood events. The yield of main crop is about 1.5 ton/rai but the second crop is much lower (about 50% of the first crop) due to insufficient irrigation. The price of corn is 3,000 THB/ton and total production cost is about 65% total production value.

Cropping systems in Chiang Saen District (downstream section of the Kok River) are mainly

- Double rice in an area near the natural lake;
- Corn and tobacco on the high land.

From the flood risk assessment and observations from the site visits, the Consultants view the Nam Mae Kok floodplain as:

1. The impact of flooding on houses and infrastructure are insignificant;
2. There is a certain level of crop damage caused by flood, however it is limited to just a narrow strip along the river;
3. Flood protection for crop in the area seems to be not economically feasible, since the high embankment needed would entail high cost of construction;
4. The irrigation facility for the area seems to be the option for providing opportunity to change land-use and crop varieties to avoid flooding;
5. The area would benefit from integrated water resource development with main components of providing irrigation water and changes in land use.

Photo 1 and 2: View at the bridge on road 1098 crossing Mae Kok midway from Chiang Rai City to the river mouth. Second crop of corn at the harvesting period.

Photo 3 and 4: View at Mae Kok River mouth: (3) Tobacco and temporary hut; (4) Corn will be harvested in April.

CHAPTER 3

SOCIAL DIMENSIONS OF FLOODING

3 SOCIAL DIMENSIONS OF FLOODING

3.1 Socio-economic Survey

The Nam Mae Kok River in Thailand has a high yearly variation in flood peaks and incidentally severe floods occur. It has been selected by the TNMC as focal area for Integrated Flood Risk Management. The area concerns the Nam Mae Kok River from Chiang Rai to its confluence with the Mekong.

The Nam Mae Kok Basin covers an area of 10,730 km^2. The length of the river from source to mouth is 360 km. Flood prone areas in the Nam Mae Kok Basin are mainly (i) Valley of Nam Mae Fang; (ii) Chiang Rai Province; and (iii) Mouth of Nam Mae Kok. In Chiang Rai Province flooding takes place near the city of Chiang Rai, located at the confluence of the Nam Mae Kok and Nam Mae Lao. The city is flood prone when the rivers convey large discharges. The last major flood of 2006 came from the Nam Mae Lao and a small creek named. Details are presented under Hydrological hazards.

Two districts in the focal area in Chiang Rai province were selected by the TNMC for social economic survey and data collection under the FMMP-C2. They are Mueang Chiang Rai and Chiang Saen. See Map.

The social surveys were conducted in the two districts: 6 villages in 3 sub-district/communes of Mueang Chiang Rai District; and 6 villages in 2 communes of Chiang Saen District. See Table 3-1.

Table 3-1 Sample of Socio-economic Survey.

District	Sub-district	Village	Household	Business
Chiang Rai	Rob Wieng	Doi Kao Kaoy	24	4
		Mae Korn	19	4
		Mae Lao Noi	21	
	San Sai	Mae Korn	25	1
	Ta Sai	Mae Lao Noi	25	4
		San Kamint	20	
Sub-total			**134**	**13**
Chiang Saen	Ban Saw	Koa Pha Kam	15	3
		San Sai Kong Ngan	15	4
		Sob Kok	15	4
	Yonok	Doi Jun	13	4
		San Tat	22	2
		San Ton Pao	10	4
Sub-total			**90**	**21**
TOTAL			**224**	**34**

Source: Socio-economic survey, Thailand

3.2 Flood protection measures

A number of flood protection measures have been taken in the target communes and districts in the focal area, as summarized below.

Table 3-2 Flood Protection Measures.

District	***Commune / Measures***
Mueang Chiang Rai	3 FGDs at Ban Tha Sai, Ban Doi Khao Khwai, and Ban Mae Korn: ▪ Flood protection measures are temporary dike embankments made from soil along 2 sides of Mae Lao River in Ban Tha Sai sub-district. ▪ Other measures were building a house on poles and improving cannels/river bank.
Chiang Saen	2 FGDs at Yonok and Ban Sop Kok communities: ▪ The area is dominated by agricultural land without any flood protection. ▪ The houses are on the hills and hard being affected by the flood.

Source: Focal Group Discussions, Thailand

3.3 What constitutes good and bad floods?

Throughout the focal area, FG participants classify a good flood as one that brings the normal flood levels and occurs in a short duration that are conducive to the growth of the rice crop, as well as more fish. A bad flood is one having high flooding depth and occurring long duration. The benefits and damages associated with good and bad floods are similar across the focal area. The following table summarizes and the degree of damage depending on the date of onset of the flood.

Table 3-3 Flood Characteristics.

Dist.	***Commune***	***Flood Benefits***	***Flood Damages***
All	All	▪ Floods provide fertility and sediment for rice fields. ▪ Lower costs for rice production i.e. fertilizers application by 7% and almost no change in pesticides application. ▪ Floods increase fish levels. ▪ People benefit from catching fish to supplement diet/make money; benefit greater in big flood year.	▪ Damage to rice crop if flood is high. ▪ Difficulty in travelling to work and school.
Timing of Flood Damages			
Mueang Chiang Rai	All	▪ Normal flood	▪ Mid September-Mid October
	All	▪ Big flood	▪ Mid August-Mid October
Chiang Saen	All	▪ Normal flood	▪ Mid August-Mid September
	All	▪ Big flood	▪

Source: Focal Group Discussions, Thailand

3.4 Community Characteristics

The characteristics of communities in the two districts surveyed in this focal area are similar in terms of population composition by age groups and by sex. Male is more than female in age group (1-14) especially in Chiang Saen District. However, the situation is reversed in other two age groups (15-60) and (more than 60).

Table 3-4 Community Characteristics, age and sex distribution.

Community Characteristics, Nam Mae Kok Focal Area, Thailand					
Age group	**Sex**	**Mueang CR**	**Chiang Saen**	**Mueang CR**	**Chiang Saen**
		(#person)	(#person)	(% of total)	(% of total)
1-14	Male	6,958	4,137	9%	10%
	Female	6,439	1,034	8%	2%
15-60	Male	28,030	15,263	36%	37%
	Female	28,667	17,557	37%	42%
60+	Male	3,305	1,591	4%	4%
	Female	3,419	1,955	4%	5%
TOTAL		76,818	41,537	100%	100%

Source: Flood Vulnerability Database, Thailand

Total population of Mueang Chiang Rai was about 77,000 persons almost double of population in Chiang Saen District. Population growth rate from 2001-2006 was 1.76% and 1.90% per year in Mueang Chiang Rai and Chiang Saen District respectively. Ethnic composition in the two selected districts are the same as 83% -Thai, 9% - Hill tribes, 1% - Chinese and 7% - others.

The residential area is located on a hill and/or high ground, therefore flooding risk for the communities is low, especially in Chiang Saen District where most villages are on the high land.

Table 3-5 Community Characteristics, ethnicity and poverty level.

Indicator		***Unit***	***Chiang Rai***	***Chiang Saen***
Population		No.	76,818	53,537
Number of HH		No.	18,870	10,685
Ethnicity	Thai	%	83%	83%
Chinese		%	1%	1%
Hill tribes		%	9%	9%
Others		%	7%	7%
Poor HH		%	n/a	n/a
Population growth, 2001-2006		%	1.76%	1.90%

Source: Flood Vulnerability Database, Thailand

3.5 Household Characteristics

Size of household was about 4 persons in Mueang Chiang Rai District and 5 persons in Chiang Saen District. Women head varies between 11-15% of the households. However, the proportion of children is low and, therefore, there are low dependency ratios. The consequences regarding vulnerability to flooding include:

(i) The proportion of female-headed households tends to indicate a higher risk of poverty compared with male-headed households. In addition, if there is a shortage of adult males in these households, women will be more vulnerable because they lack labour.

(ii) The low proportion of children and low dependency ratios will decrease vulnerability of households. Children are frequently most at risk, for example, drowning in floodwaters or becoming sick from drinking and/or exposure to contaminated water.

Table 3-6 Household Characteristics.

Indicator		***Unit***	***Chiang Rai***	***Chiang Saen***
HH size (average)		Pers.	4.07	5.01
HH head	Male	%	85%	89%
Female		%	15%	11%
Male/female ratio			5.49	7.79
Children < 15 years		%	17.4%	9.7%
Dependency ratio			0.26	0.16

Source: Flood Vulnerability Database, Thailand

3.6 Land Use and Tenure

The largest land use in each district in the focal area is forest land (about 45% in Mueang Chiang Rai District and 54% in Chiang Saen District. irrigated rice land. There is almost no irrigated rice land in Chiang Saen and there is only a small area of rice land irrigated in Mueang Chiang Rai District. Rain-fed rice land occupies 20% and 10% of the total land area in Mueang Chiang Rai and Chiang Saen.

Table 3-7 Land Use.

Indicator	***Unit***	***Chiang Rai***	***Chiang Saen***
Rice Land – Irrigated	%	2%	
Rice Land - Not irrigated or rain-fed	%	20%	10%
Crop Land	%	13%	9%
Plantation Land	%	10%	22%
Residential - Rural (including gardens)	%	3%	1%
Residential – Urban	%	3%	0.2%
Commercial / Industrial	%	0.22%	0.01%
Institution	%	1%	0.02%
Forest	%	45%	54%
Communal land	%	2%	4%

Source: Flood Vulnerability Database, Thailand

Households depend on agricultural economic activities with implications for social vulnerability to flooding including:

(i) The reliance of livelihoods on agricultural land increases the direct and indirect costs of flooding. Household expenditures for food and other basic needs will increase if people are unable to cultivate paddy or vegetables in the fields/ gardens; incomes decrease from the loss of crop sales.

(ii) The lack of flood protection measures to crop cultivation and agricultural production during the flood season increase the flooding risk for agricultural households.

(iii) People in remote areas are the most vulnerable groups due to limited access to flooding information and prevention measures.

3.7 Houses and other structures

There is no information on houses and structures available at a district level, except the information collected in the household and business sample survey.

Table 3-8 Housing/Structure Characteristics.

Indicator	***Unit***	***Chiang Rai***	***Chiang Saen***
Residential - % total	%	n/a	n/a
permanent	%	n/a	n/a
semi-permanent	%	n/a	n/a
temporary	%	n/a	n/a
Commercial - % total	%	n/a	n/a
permanent	%	n/a	n/a
semi-permanent	%	n/a	n/a
Industrial - % total	%	n/a	n/a
permanent	%	n/a	n/a
semi-permanent	%	n/a	n/a
Institution - % total	%	n/a	n/a
permanent	%	n/a	n/a
semi-permanent	%	n/a	n/a

Source: Flood Vulnerability Database, Thailand

The average area and value of housing varies significantly among the two selected districts but construction cost was in-order of 5,000 THB per m^2. The average hose area is 117 m^2 in Mueang Chiang Rai District which is bigger than those in Chiang Saen District. Most of houses in the focal area are classified as permanent.

Table 3-9 Housing Area & Value.

Housing Area & Value		***Chiang Rai***			***Chiang Saen***		
		%	*Area*	*Value*	*%*	*Area*	*Value*
		HH	*m^2*	*1,000 THB*	*HH*	*m^2*	*1,000 THB*
Overall	Average		117	577		81	393
By house type	Permanent	92%	116	591	93%	81	401
	Semi-Permanent	7%	121	416	7%	82	273
	Temporary	1%	160	550	-	-	-

Source: Household surveys

(i) In the focal area, households are located in villages where ground level is high and the impact of flood is low.

(ii) In lower areas, people built their house on poles or on highly raised foundation to reduce the flood risk.

(iii) Shop owners will employ similar methods, such as raising the foundation of the shop structure and making sure that it is possible to shift inventory and equipment to high levels within the structures.

In-short, the implications for the vulnerability of households and businesses to flooding is low.

3.8 Household assets

There was no information available to the survey team from district statistic data.

Table 3-10 Household Assets.

Indicator	***Unit***	***Chiang Rai***	***Chiang Saen***
Number of HH	No.	18,870	10,685
Motorbike (1 or more)	%	n/a	n/a
Car /truck	%	n/a	n/a
Small boat (without engine)	%	n/a	n/a
Large boat (with engine)	%	n/a	n/a
Mechanized tractor	%	n/a	n/a
hand tractor	%	n/a	n/a
Water pump	%	n/a	n/a
Rice cutting & threshing	%	n/a	n/a
Rice drying	%	n/a	n/a
Rice planting	%	n/a	n/a

Source: Flood Vulnerability Database, Thailand

3.9 Rural livelihoods

Rural livelihoods are based on the cultivation of rice mainly rain-fed, except a small area (12% of rice land) in Mueang Chiang Rai is under irrigation. The rice cultivation area occupies 62% in Mueang Chiang Rai and 47% in Chiang Saen. The remaining land is cultivated upland crops (corn, pineapple, cassava, and vegetables).

Throughout the focal area, the average holding of rice paddy is about 2.2 ha in Mueang Chiang Rai District and 18.1 ha in Chiang Saen District. The households that live in permanent and semi-permanent houses tend to have holdings that are 2-3 times larger than those belonging to households living in temporary structures. The average yields are high in Mueang Chiang Rai District (4.4 ton/ha) and much lower in Chiang Saen District (2.8 ton/ha). It is observed that their rice production sold to market is more than 80% of total (harvested) production, especially farmer in Mueang Chiang Rai District even sold more than 90%.

Table 3-11 Production & Income.

Production & Income		**Chiang Rai**			**Chiang Saen**		
		Paddy Area	***Prod. Sold***	***Annual Income***	***Paddy Area***	***Prod. Sold***	***Annual Income***
		ha	*%*	*THB million*	*ha*	*%*	*THB million*
Overall	Average	2.2	92%	n/a	18.1	84%	n/a
By house type	Permanent	2.1	92%	n/a	18.7	84%	n/a
	Semi-Permanent	3.5	90%	n/a	8.8	87%	n/a
	Temporary	0.8	95%	n/a			

Source: Household Surveys, Thailand

A range of vegetables and other crops are grown throughout the year in gardens located adjacent to houses and in other locations on a high land

Although rice cultivation is the primary occupation, many households have other non-agricultural income sources from livestock and raising fish. The survey showed that 25% of household in Chiang Saen District whose fish pond affected by flood 2006.

3.10 Access to electricity, water and sanitation

There is limited data and information available in the focal area. In Mueang Chiang Rai District, there is a high level of access to grid electricity 97% of household and about 1% connecting to private electricity source. There are still approximately 2% of the households that do not have electricity.

There are six public piped water systems in Mueang Chiang Rai District covering 80% of households. There is no data available on this in Chiang Saen District.

Table 3-12 Access to Services.

Indicator	*Unit*	*Chiang Rai*	*Chiang Saen*
Number HH	No.	18,870	10,685
Electricity			
HH - public grid	%	97%	n/a
HH - no electricity	%	2%	n/a
Water and sanitation			
Public piped systems	No.	6	n/a
HH connected	%	80%	n/a
Private piped systems	No.	n/a	n/a
HH connected	%	n/a	n/a
Non-piped water supply			
Private wells (HH)	%	n/a	n/a
Rainwater (HH)	%	n/a	n/a
Sewered WW systems	No.	2	n/a
HH connected	%	n/a	n/a
Private latrines – HH	%	n/a	n/a

Source: Flood Vulnerability Database, Thailand

The higher the proportion of households that has access to safe drinking water and adequate sanitation, the lower the risk of illness and disease. Notwithstanding, in this focal area, FG participants have indicated that there is increased incidence of diarrhoea and dysentery during the flood period that is the result of contaminated water and inadequate sanitation.

3.11 Access to health care

In general, there is at least one hospital and one health clinic in each district in the focal area. A number of dispensaries are easily accessible to most households. There is significant different in a level of access to health care between Mueang Chiang Rai and Chiang Saen District. The limited health care services are observed in Chiang Saen District through high health care indicator.

Table 3-13 Access to Health Care.

Indicator	*Unit*	*Chiang Rai*	*Chiang Saen*
Population/hospital bed	ratio	68	892
HH/clinic	ratio	173	822
HH/dispensary	ratio	185	2671

Source: Flood Vulnerability Database, Thailand

The implications for people's social vulnerability during floods are:

(i) The number, distribution and resources of health care facilities are important assets during floods when people have special needs to obtain health services and medications. This tends to increase the resilience of households and communities to deal with the health impacts of flooding, especially in Chiang Saen District.

3.12 Flood warning, emergency response and recovery

(i) Flood warning: There is public relation in villages through village air radio operated by head of villages/ local Administration authority. This activity will make announcement/ warning when water level is increasing. Then, people in the communities can get information from this announcement directly and it covers the whole area. The village air radio will make warning in advance 2 days before flooding. Thus, this system is a strong point. Moreover, the communities can get the weather forecasting from television and radio national network as well.

(ii) Emergency response to flooding: Amphoe (District) will provide information on emergency warning to sub-districts (villages) for making announcement. At provincial level, there are coordination among various relevant agencies (Royal Irrigation Department office in province, Office of Water Resources, DDPM, and other NGOs) to support/rescue local communities to eliminate the losses cause by flooding.

(iii) Recovery after flooding: There are no plans/strategies to recover after flooding. However, during flooding or after the events government pays for compensation. Such government supports have eliminated the harness and difficulties of communities suffering from flooding.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4 CONCLUSIONS AND RECOMMENDATIONS

Based on the analyses presented in the previous chapters the following conclusions can be drawn.

1 Flood prone area in the Nam Mae Kok Basin comprise:
- Valley of Nam Mae Fang River;
- Chiang Rai Province, and;
- Mouth of Nam Mae Kok River.

2 Floods in the upper reaches of the tributaries are flashy. Flashiness decreases further downstream in the Chiang Rai region. In the lower 20-25 km of the Nam Mae Kok near the mouth the flood levels are affected by backwater from the Mekong.

3 Extreme value distributions of peak flows and the possible range of flood volumes can be used for assessment of the hydrological hazard in the Chiang Rai region regarding peak levels and flood duration. A bivariate distribution for the river mouth.

4 Water level and discharge series of sufficient length are available for assessing the hydrological hazard in the Chiang Rai region and near the Nam Mae Kok mouth.

5 Validation of hydrological data does not appear to be common practice according to sources at the data collecting agencies.

6 The applied stage-discharge relations for the stations on Nam Mae Kok and tributaries varied strongly from year to year. The number of discharge measurement taken each year suggests that the changes are due to morphological developments in the station controls. Some re-settings of gauges to different gauge zeros seem to have occurred, but have not been recorded.

7 Whereas the rainfall records are mutually consistent, the discharge series are not. Distinct changes in the records are apparent in the series of Ban Pang Na Kham in the period 1988-1994, whereas the series of Ban Mae Phaeng is inconsistent with the area adjusted sum of the Kok and Lao flows for almost its entire record.

8 As a consequence of the Ban Mae Phaeng inconsistency, the SWAT based lateral inflows are overestimated by a factor 2.3.

9 Annual rainfall in the Kok Basin is largest towards the river mouth (1,700 mm) with lower values of 1,300 to 1,400 mm in the upper reaches of the Nam Mae Kok and the Nam Mae Fang. Rainfall is highest in the months July-September

10 Evaporation peaks in April-May. Annual totals vary from 1,300 to 1,500 mm. It exceeds rainfall in the period November-April.

11 The annual average flow volume of the Nam Mae Kok at mouth is about 5.24 BCM. Runoff of Nam Mae Kok at Chiang Rai per unit area is twice the runoff of the Nam Mae Lao. At Chiang Rai the runoff is highest in the months August and September, whereas in Nam Mae Lao September is the month with the largest flow volume.

12 The regime of the Nam Mae Kok is a few weeks in spate relative to the Mekong regime.

13 The hydrological hazard expressed as extreme discharge for selected return periods with a full range of flood volumes have been determined for the Nam Mae Kok at Ban Pong Na

Kham, the Nam Mae Lao at Ban Pong Pu Fuang and the Nam Mae Kok downstream of the Loa confluence. Generally, the GEV fits best to the data, but due to the limited data length the EV1 is not rejected as an alternative.

14 The annual discharge peaks on the Nam Mae Kok at Ban Pong Na Kham and the Nam Mae Lao at Ban Pong Pu Fuang do generally not occur at the same time. This should be included in the selected boundary conditions for flood hazard assessment with the hydraulic model.

15 EV1 and GEV distributions fit well to the marginal distributions of observed annual maximum flood peaks and annual flood volumes in the Mekong at Chiang Saen.

16 The bivariate distribution of annual flood peaks and flood volumes in the Mekong at Chiang Saen can be described by regression equations and GEV-distributions for the regression residuals.

17 The observed distribution of annual flood volumes in the Nam Mae Kok is well described by an EV-1-distribution.

18 The bivariate distribution of annual flood peaks and flood volumes in the Nam Mae Kok at mouth can be described by regression equations and GEV-distributions for the regression residuals.

19 Neither the peak discharges nor the annual flood volumes in the Mekong versus the Nam Mae Kok show significant correlation.

20 The annual maximum discharges on the Mekong occur on average about two weeks earlier than the annual peaks on the Nam Mae Kok. Flood hazard.

21 The flooding around Chiang Rai City is complex and its extent is preferably modelled with a 1D2D hydraulic model.

22 The existing hydraulic model of the Nam Mae Kok needs to be adjusted in the cross-sections particularly for the Lao and recalibrated using appropriate lateral inflows for reliable flood hazard assessment.

23 A full range of hydrographs (flood peaks and related range of flood volumes) have been developed for flood hazard computations around Chiang Rai City.

24 Some 150 combinations of water level hydrographs for the Mekong at Sop Kok and discharge hydrographs of the Nam Mae Kok at mouth will be required for flood simulation near the river mouth as input to the Monte Carlo technique to establish the flood maps of required return periods.

APPENDICES

Appendix 1

Direct Flood Damage Inventory

Appendix 1.1 Direct flood damage inventory, Mueang Chiang Rai District.

Types	Items	Unit	Year: 2003		Year: 2004		Year: 2005		Year: 2006		Year: 2007		Year:2008	
			Quantity	Cost (THB)	Quantity	Cost (THB)	Quantity	Cost (THB)	Quantity	Cost (THB)	Quantity	Cost (THB)	Quantity	Cost (THB)
Human	Number of causalities	Person	0		0		0		0		0		0	
	Number of affected households	Family	1,812		3,388		773		310		384		90	
	Number of affected people	Person	5,721		10,661		2,136		851		1,116		360	
Housing	Collapsed/swept away houses	Nos	0	0	0	0	0	0	0	0	0	0	0	0
	Partly damaged or submersed houses	Nos	286	1,949,976	379	4,574,043	121	1,427,627	34	124,780	42	383,750	17	111,266
Agriculture	Damaged rice area	Rai	6,566	31,556,196	13,298	63,910,188	2,917	14,019,102	879	4,224,474	152	730,512	266	1,278,396
	Damaged field crops	Rai	1,206	4,868,622	3,131	12,639,847	749	3,023,713	563	2,272,831	1,661	6,705,457	33	133,221
	Damaged plantation and other	Rai	5	109,560	10	219,120	55	1,205,160	4	87,648	7	153,384	0	0
Fishery	Aquaculture pond effected	Rai	1,250	8,500,479	546	4,040,690	901	6,757,190	87	643,160	62	564,253	16	154,917
Education			No Damage		No Damage		No Damage		2	0	No Damage		No Damage	
Health care			No Damage		No Damage		No Damage		No Damage	0	No Damage		No Damage	
Structures			No Damage		No Damage		No Damage		No Damage	0	No Damage		No Damage	
Irrigation			No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
Transport	Damaged roads	Meter	980	2,147,579	2,438	4,856,652	526	1,370,972	249	764,226	45	119,622	83	234,609
	Damaged bridges/culverts	Nos	2	750,453	3	1,243,760	1	418,923	No Damage	0	No Damage	0	No Damage	0
	Damaged others	Nos	No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
Post & Telecom			No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
Industry			No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
Construction			No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
Water & Sanitation			No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
			(1000 USD)	**(1000 THB)**	**(1000 USD)**	**(1000 THB)**	**(1000 USD)**	**(1000 THB)**	**(1000 USD)**	**(1000 THB)**	**(1000 USD)**	**(1000 THB)**	**(1000 USD)**	**(1000 THB)**
	Grand Total		1,425	49,883	2,614	91,484	806	28,223	232	8,117	247	8,657	55	1,912
	Direct damages Housing		56	1,950	131	4,574	41	1,428	4	125	11	384	3	111
	Direct Damages Agriculture		1,287	45,035	2,309	80,810	714	25,005	207	7,228	233	8,154	45	1,567
	Relief&emergency		0	0	0	0	0	0	0	0	0	0	0	0
	Infrastructures		83	2,898	174	6,100	51	1,790	22	764	3	120	7	235

Appendix 1.2 Direct flood damage inventory, Chiang Saen District.

Types	Items	Unit	Year: 2003		Year: 2004		Year: 2005		Year: 2006		Year: 2007		Year:2008	
			Quantity	Cost (THB)	Quantity	Cost (THB)	Quantity	Cost (THB)	Quantity	Cost (THB)	Quantity	Cost (THB)	Quantity	Cost (THB)
Human	Number of causalities	Person	0		0		0		0		0		0	
	Number of affected households	Family	544		739		1,272		2,215		941		2,107	
	Number of affected people	Person	1,557		2,286		4,149		7,627		3,359		5,771	
Housing	Collapsed/swept away houses	Nos	0		0		0		0		0		0	
	Partly damaged	Nos	97	281,507	120	650,180	193	1,159,513	375	2,727,051	134	920,992	326	2,591,144
Agro-forest	Damaged rice area	Rai	4,670	22,444,020	6,369	30,609,414	2,879	13,836,474	6,896	33,142,176	2,393	11,500,758	5,989	28,783,134
	Damaged field crops	Rai	392	1,582,504	597	2,410,089	3,120	12,595,440	3,171	12,801,327	4,394	17,738,578	6,577	26,551,349
	Damaged plantation and other	Rai	18	394,416	26	569,712	100	2,191,200	1,317	28,858,104	167	3,659,304	400	8,764,800
Fishery	Aquaculture pond effected		168	1,289,750	144	1,067,450	158	1,178,200	333	2,465,475	105	991,596	152	1,427,813
Education			No Damage		No Damage		No Damage		2	0	No Damage		No Damage	
Health care			No Damage		No Damage		No Damage		No Damage	0	No Damage		No Damage	
Structures			No Damage		No Damage		No Damage		No Damage	0	0		0	
Irrigation			No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
Transport	Damaged roads	Meter	370	552,791	487	742,357	259	344,239	509.00	846,841	205	331,532	452	671,902
	Damaged bridges/culverts	Nos	2	798,690	3	1,210,875	1	494,702	1	462,408	1	509,089	2	732,311
	Damaged others	Nos	No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
Post & Telecom			No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
Industry			No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
Construction			No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
Water & sanitation			No Damage		No Damage		No Damage		No Damage		No Damage		No Damage	
			(1000 USD)	(1000 THB)	(1000 USD)	(1000 THB)	(1000 USD)	(1000 THB)	(1000 USD)	(1000 THB)	(1000 USD)	(1000 THB)	(1000 USD)	(1000 THB)
	Grand Total		781	27,344	1,065	37,260	909	31,800	2,323	81,303	1,019	35,652	1,986	69,522
	Direct damages Housing		8	282	19	650	33	1,160	78	2,727	26	921	74	2,591
	Direct Damages Agriculture		735	25,711	990	34,657	851	29,801	2,208	77,267	968	33,890	1,872	65,527
	Relief&emergency		0	0	0	0	0	0	0	0	0	0	0	0
	Infrastructures		39	1,351	56	1,953	24	839	37	1,309	24	841	40	1,404

Appendix 2

Methods for the Economic Valuation of Loss of Life

Methods for the economic valuation of loss of life

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ABSTRACT: In risk management literature the economic valuation of loss of life is often depicted as a difficult question as it raises numerous ethical and moral questions. The actual investments in risk reduction are however always finite, indicating that the implicit value assigned to loss of human life is finite. In this paper, an overview of methods for the valuation of human life is presented. The backgrounds and basic assumptions of the different methods are discussed. Two distinct approaches can be discerned: behavioural and non-behavioural valuation methods. Non-behavioural approaches can be divided into stated and revealed preference methods. The different approaches lead to distinctly different valuations of human life. Loss of life will generally be a marginal cost item in a societal cost-benefit analyses for hazardous industrial activities due to stringent risk regulations that have resulted in a low probability of harm to humans. For such cost-benefit analyses it is therefore proposed to present loss of life separately and to weigh it politically against the net financial balance.

1 INTRODUCTION

As a society without risk is impossible, risk regulation is to maintain the delicate balance between socio-economic development and a safe society. This paper focuses on the use of cost-benefit analysis for the management of large-scale risks associated with industrial hazards in the Netherlands.

In the Netherlands, regulations for land-use planning in the vicinity of major industrial hazards are explicitly risk-based. In risk-based regulation, not only potential adverse physical effects are considered but also the probability of failure. Three main elements constitute the Dutch regulatory framework: (i) quantitative risk assessment, (ii) the adoption of individual and societal risk as risk-determining parameters and (iii) acceptability criteria for individual and societal risk [1]. Besides these criteria, the ALARA-principle is adopted. Also when the risk criteria are met, risks should be reduced to levels that are as low as reasonably achievable. Whether additional investments in risk reduction are reasonable is determined by implicit or explicit societal cost-benefit analysis.

Investments in safety require a trade-off between the costs of risk reduction and the benefits thus obtained. Cost-benefit analysis is a useful tool for comparing the costs and benefits of an activity or action. In cost-benefit analyses, both costs and benefits are expressed in a single unit, commonly currency. This poses some difficulties in risk regulation since the benefits of a risk reducing prospect might not easily be expressed in monetary terms. When potential damages include loss of life, a benchmark value would have to be adopted for the value of human life. For instance, UK's Health and Safety Executive has adopted a benchmark value of preventing a fatality of one million pounds for industrial safety [2]. This value is derived from the Department of Transport, Local Government and the Regions (DLTR). In case death is caused by cancer a value of preventing a fatality of two million pounds is used. Official values of preventing a fatality in road safety range from less than 100.000 euros to about 3.5 million euros [3]. These values can however not simply be extrapolated to industrial safety.

In literature on risk management the valuation of human life is often depicted as a difficult problem as it raises numerous moral questions. Some claim it is unethical to put a price on human life and that life is priceless. The actual expenditures on risk reducing prospects show however that the investment in the reduction of risks to humans is always finite. In this paper the term “valuation of human life” is adopted to signify the implicit or explicit investment in reduction of loss of human life.

This paper presents an overview of the backgrounds, basic assumptions, strengths and criticisms of the various methods for the valuation of loss life. A distinction can be made between behavioural and non-behavioural valuation methods [4]. Behavioural valuation is based on micro-economic theory and assumes utility maximizing individuals. Two behavioural approaches can be discerned: stated preference and revealed preference methods. Non-behavioural valuation is based on an individual's productivity and opportunity cost.

2 INVESTING IN SAFETY

Investments in safety require a trade-off between the costs of risk reduction and benefits thus obtained. Societal cost-benefit analysis (SCBA) is a method for comparing the societal costs and benefits of an economic activity. The Netherlands Bureau of Economic Policy Analysis has concluded that a cost-benefit analysis is a suitable instrument in the field or industrial safety for proper mapping of the effects of alternatives [5]. From an economic perspective, an option is preferable over other when it has the highest expected value of benefits of all options, or:

$$Max\left(B_i - P_{fi} \cdot C_i\right) \quad (1)$$

where B_i = benefit produced by option i; P_f = probability of failure of option i; C = cost associated with failure of option i

Using a similar expression, one could state that an activity is beneficial when its net expected value of the financial balance is positive. Cost-benefit analysis can also be used as a method for evaluating the cost-effectiveness of investments in risk reduction. The benefit of these investments consists of the reduction of the expected value of the costs of failure. The economically optimal investment is:

$$Min\left(I(P_f) + P_f \cdot C\right) \quad (2)$$

where $I(P_f)$ = investment in risk reduction; P_f = probability of failure; C = cost associated with failure

Economic optimization has been used to determine the optimal investment in flood protection in the Netherlands [6]. Because the economic value of dike ring areas varies considerably, design standards and hence probabilities of flood vary across dike ring areas [7]. In the economic optimization of the flood defences, only material damages were taken into account and loss of life was not valued in monetary terms [6].

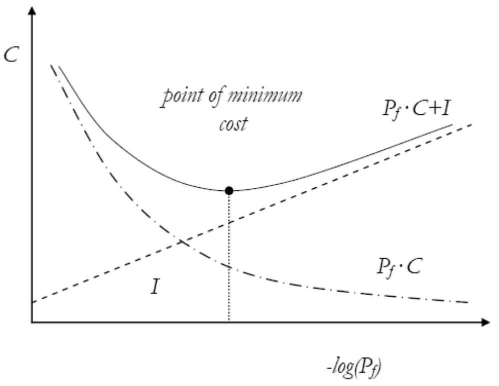

Figure 34 The economically optimal probability of failure (adapted from [8])

Valuation of loss of life might be relevant for the economically optimal investment flood safety. Depending on the probability and extent of material damages given failure and the probability of death given failure, assigning a value to a statistical life in the order of one million euros could result in a lower economically optimal probability of failure.

Industrial activities are initiated to generate economic benefits rather than to control natural hazards. For these technological systems, such as chemical installations, risks to human life are generally a marginal item in the outcome of a societal cost-benefit analysis for the activity as a whole. This is because regulations ensure that the probability of harm is already low [1].

In the Netherlands, industrial risks are evaluated from an individual and a societal perspective. The individual perspective is to ensure that no individual is disproportionally exposed. It is defined as the probability of death of an average, unprotected person that is ever-present at a certain location. Individual risk is limited by law to 10^{-6} per year for new installations [9]. The societal perspective reflects that society as a whole does not appear to accept the too frequent occurrence of large accidents. For this purpose, an FN-criterion has been adopted. An FN-criterion prescribes maximum exceedance frequencies of accidents with N fatalities. The Dutch criterion is $10^{-3}/N^2$ per installation per year (where N is the number of fatalities in an accident).

Risk regulation has thus resulted in very low probabilities of loss of life. Because of the low probability of harm, the cost assigned to loss of life will have to be enormous if the costs of failure are to outweigh the benefits of the hazardous activity as a whole. It thus seems important to make a distinction between economic optimizations of risk control systems and cost-benefit analyses for industrial activities as a whole.

3 BEHAVIOURAL VALUATION: STATED PREFERENCE

The main example of the stated preference approach is contingent valuation. It is a method in which people's willingness to pay for an intangible loss is determined by creating an artificial market and asking respondents to value the availability of that asset. An influential report on contingent valuation was written by the NOAA Panel [10] in which guidelines were presented for performing contingent valuation studies for estimating the passive-use value of environmental resources. The method has also been applied to determine the willingness to pay for risk reduction, e.g. the reduction of flood risk [11].

The societal willingness to pay can be found by aggregating all individual *WTPs* of the respondents and by extrapolating the results to the selected population:

$$SWTP_{CV} = \frac{V}{\mathrm{R}} \sum_{j=1}^{\mathrm{R}} WTP_j \tag{3}$$

where WTP_j = willingness to pay of respondent j; R = number of respondents; V = relevant population

Subsequently the value of a statistical life ($VoSL_{CV}$) can be calculated according to:

$$VoSL_{CV} = \frac{V}{\mathrm{R}} \sum_{j=1}^{\mathrm{R}} \frac{WTP_j \cdot LE}{\mathrm{R} \cdot \Delta LE} \tag{4}$$

where WTP_j = willingness to pay of respondent j; LE = life expectancy; V = relevant population; R = number of respondents; ΔLE = change in life expectancy averaged over the age-distribution of the population

Contingent valuation includes risk perception in the valuation of life as the outcome is based on individual preferences. Risk perception depends on several characteristics of the hazard and risk under consideration [e.g. 12, 13, 14]. The method therefore values loss of life differently across a range of different hazards. One may consider this irrational but it expresses the importance of a fundamental aspect of the human condition: emotion.

Contingent valuation has received considerable criticisms [15]:

1 Contingent valuation surveys don't measure preferences correctly because respondents are not affected by budget constraints. Answers are given to hypothetical questions. Thus strategic and affective ('warm glow') behaviour confuse the results.

2 The results appear to strongly depend on context and phrasing [see also 16]. This is related to the strong cognitive demands that are paced on respondents. That temporal stability as a measure of the reliability of WTP is insufficient [11] supports this notion.

3 Studies have shown that WTP is rather insensitive to the quantity of the asset for which the value is to be determined. A study by Geurts et al. [11] shows that scope validity is ambiguous.

4 The willingness to accept appears to be considerably larger than the willingness to pay [see also 16]. The compensation a respondent would wish to receive for accepting a loss thus differs considerably from his willingness to pay for preservation of the same good.

5 A practical problem with contingent valuation is deciding on the size of the relevant market. Who should belong to the respondents? The willingness to pay for flood protection is likely to depend on the level of exposure of the respondent. However, non-exposed people could value the safety of others. If the number of respondents is enlarged, the aggregate willingness to pay will increase.

6 The non-neutral character of money can make the aggregation of individual preferences dependent on the choice of the numéraire. When the marginal rates of substitution between a public and a private good are not the same for all consumers, the outcome of a cost-benefit analysis is determined by the choice of the unit of aggregation. A change of sign of the sum of net benefits can occur when a different unit is chosen. The non-neutral character of money makes it questionable to aggregate costs and benefits of different involved parties in cost-benefit analyses without weighing [15]. A person that attributes relatively low value to money is systematically favoured when money is chosen as the numéraire in the cost-benefit analysis. The dependency on the choice of numéraire is the result of the fact that it not only normalizes prices but also marginal utilities [17].

4 BEHAVIOURAL VALUATION: REVEALED PREFERENCE

Revealed preference methods are based on the assumption that economic behaviour reflects the values implicitly assigned to intangibles. For instance, compensating wage differentials for more dangerous professions could be assumed to reflect people's willingness to accept (WTA) certain occupational risks.

In the field of industrial safety, property values in the vicinity of industrial hazards could be said to reflect willingness to accept. However, property values are probably mainly influenced by view, noise and other nuisances rather than the remote probability of catastrophic events. For industrial safety, a crude method could be to assume that accident statistics reflect acceptable levels of residual risk.

Then, the investment that has been made for the prevention of potential loss of life can be expressed as the cost of saving an extra statistical life (CSX). Past expenditures on life saving prospects can be used to calculate CSX-values. CSX-values indicate the apparent economic value attached to loss of life. The cost of saving an extra life year (CSXY) can be calculated by introducing the life expectancy. When calculating the value of a statistical rather than an actual life, the *CSXY*-values should be multiplied with the life expectancy at birth:

$$VoSL_{CSX} = CSX = CSXY \cdot LE \qquad (5)$$

where LE = life expectancy at birth

It is important to use net costs as material damages and other intangible losses than loss of life also influence economic behaviour [18]. For example, investments in the prevention of radionuclide-emissions not only reduce the probability of premature deaths but also the probability of injuries and severe pollution. It is now impossible to derive a unique solution for the cost of saving a statistical life.

CSX(Y)-values vary widely not only between but also within risk categories [19]. Sensitivity analysis is unlikely to provide a way out since the variance is in several orders of magnitude.

Other objections to revealed preference methods are targeted at the assumptions underlying the method. First, the assumption that equilibrium has been reached and that this equilibrium is acceptable may be questionable [20]. The expected number of casualties in traffic in the Netherlands is approximately 1000 per year. The efforts of 3VO, a Dutch NGO concerned with safe traffic, indicate however that this level is not yet acceptable. Secondly, revealed preference methods have the questionable assumption that preferences are stable. Public investments in safety are highly influenced by actual calamities. The investments are then made when public concern is unusually high.

5 NON-BEHAVIOURAL VALUATION

When the economic value assigned to loss of life is only based on an individual's potential economic production, this method is referred to as a human-capital approach [21]. For determining a person's productivity, macro-economic indicators could be used. By Vrijling et al. [22] it is proposed to use the net national product per capita as a basis for the valuation of human life. According to that method, named here macro-economic valuation, the societal willingness to pay for a change in life expectancy would be:

$$SWTP_{MEV} = V \cdot d(NNP^*) \approx V \cdot NNP^* \cdot \frac{d(le)}{LE} \qquad (6)$$

where: V = population size; NNP^* = present value of net national product per capita averaged over the age-distribution of the national population; $d(le)$ = change in life expectancy averaged over the age-distribution of the national population; LE = life expectancy averaged over the age-distribution of the national population

The value of a statistical life depends on the age-distribution of the national population. As an approximation a uniform age-distribution is assumed. In the Netherlands, assuming a net national product per capita of 23.000 euros, a life expectancy of 78 years and a discount rate of 4% a value of a statistical life of about 400.000 euros is found. Due to the typical skewness of the age-distribution, this value is a lower limit. The upper limit of the value of a statistical life according to macro-economic valuation can be found by assuming the life expectancy at birth for the entire population. This upper limit is about 550.000 euros. The VoSL-estimate based on macro-economic valuation will thus be in the order of 0.5 million euros.

The introduction of economic growth would result in a higher value of a statistical life. Ramsberg [21] points out that a person's contribution to the national economy should be calculated by discounting the production minus consumption over the years the person had lived if he hadn't died. Then, even lower values than 0.5 million euros are obtained.

It might be considered unethical that the value assigned to human life by non-behavioural valuation depends on a nation's wealth. The purchasing power in wealthier and poorer countries varies considerably however. Moreover, it can be considered an advantage that the value of a statistical life depends on the net national product as it ensures that risk reduction measures are affordable in the context of the national economy [22]. Another advantage of macro-economic valuation is that macro-economic indicators are relatively stable. Stability over time of VoSL-estimates is a desirable property for cost-benefit analyses as investment projects generally have a life-span of many years. If the value would change considerably over time, the economic optimization would have to be repeated regularly.

A disadvantage of macro-economic valuation is that people are only seen as factors of production: life quality is not valued. A non-behavioural method for the economic valuation of loss of life that explicitly takes life quality into account is provided by the life quality index (LQI). The LQI is a social indicator of life quality [23]. It provides a rationale for the amount of money that can be considered reasonable for a certain amount of risk reduction. The results will be shown to be very similar to those of the previously described macro-economic valuation method. The LQI is equivalent to a utility function and has the following form [24, 25]:

$$LQI = G^{q} \cdot E \quad \text{where} \quad q = \frac{w}{1-w} \tag{7}$$

where: G = real gross domestic product per capita; q = ratio of average work to leisure time available; w = fraction of time spent working; E = discounted life expectancy averaged over the age-distribution of the national population

The basic thoughts underlying the LQI-methodology are that only leisure time and consumption provide utility and that available time and wealth are exchangeable [23]. Investments in risk reduction will have a negative impact on the gross domestic product but a positive impact on the life expectancy. A trade-off has to be made between consumption and life expectancy. The consumption rate is assumed constant and equivalent to the gross domestic product per year. The exponent q is the elasticity of marginal utility with respect to consumption. It is equivalent to the ratio of average work to leisure time available and assumed constant for all levels of consumption.

As the assumption is made that production equals consumption, the trade-off is essentially between the increase in life expectancy and the increase in work time required to pay for risk reduction. Years worked is thus a substitute for death, an extremely negative value judgment. A non-zero utility for years worked would imply that people are willing to work longer and thus pay more for the same risk reduction measure.

The yearly societal willingness to pay for an increase in life expectancy of a person can be shown to be equal to [25]:

$$SWTP_{LQI} = \frac{V \cdot G}{q} \cdot \frac{d(e)}{E} \tag{8}$$

where: V = population size; G = gross domestic product per capita; q = ratio of average work to leisure time available; $d(e)$ = change in discounted life expectancy averaged over the age-distribution of the national population; E = discounted life expectancy averaged over the age-distribution of the national population

In macro-economic valuation, the net national product was used instead of the gross domestic product. The gross domestic product is the total value of all goods and services produced domestically in a year. The net national product is equal to the gross national product after adjusting for the depreciation of capital. A national product also includes production by factors of production outside a state's borders whereas a domestic product confines itself to production within a state's borders. When the difference between net national and gross domestic product is disregarded a more insightful comparison of the macro-economic/human capital and life quality index valuation methods can be made. To do so the GDP is adopted as the measure of productivity in macro-economic valuation.

According to macro economic valuation, the societal willingness to pay for an increase of life expectancy would now be:

$$SWTP_{MEV} = V \cdot G{*} \cdot d(le) \tag{9}$$

where: $G*$ = net present value of the total gross domestic product per capita in remaining life span averaged over the age-distribution of the national population

The societal willingness to pay according to macro-economic valuation appears to be somewhat similar to the yearly societal willingness to pay according to the LQI. Besides the fact that the LQI gives a societal willingness to pay per year, the results differ in two respects. First, in the LQI-method a factor $(q \cdot E)$ is present that resembles the amount of discounted life years the person is expected to spend working. Secondly, in macro-economic valuation, discounting is applied to the gross national product, whereas discounting is applied to the life expectancy in the life quality methodology. It should be noted however that the discount operator in the LQI originally belonged to the utility of consumption and was applied to life expectancy for reasons of mathematical simplicity.

These two differences will now be evaluated. Consider a society of only one person that is 40 years old. Assume that this person has a life expectancy of 80 years. The maximum amount of money that would be spent on a risk reducing prospect that would result in an extension of this person's life expectancy with one year according to macro-economic valuation is:

$$SWTP_{MEV} = \frac{G}{(1+r)^{(81-40)}} = \frac{G}{(1+r)^{41}} \tag{10}$$

where: G = gross domestic product per capita per year; r = discount rate

According to the LQI-methodology, the societal willingness to pay can also be calculated. An important difference however is that this is a societal willingness to pay *per year*:

$$SWTP_{LQI} = \frac{1}{q \cdot E_i} \frac{G}{(1+r)^{41}} \qquad (11)$$

where: G = gross domestic product per capita per year; r = discount rate; E_i = discounted life expectancy of the person under consideration

We could repeat this exercise for every person and derive the societal willingness to pay averaged over the age-distribution of the national population. For illustrating the differences between both methodologies this is however unimportant.

Whether discounting is applied to the change in life expectancy or productivity appears to be insignificant as was to be expected. The net present value of utility decreases similarly over time in both approaches because the discount rate is the same since 'we must discount future risk at the same rate as money' [23: 80]. The utility in terms of productivity (G) changes one unit per year, as does the utility in terms of life years. Besides the fact that the LQI-method gives yearly SWTP-values, the only difference between the macro-economic/human capital method and LQI-method appears to be the factor ($q \cdot E$) which resembles the amount of discounted life years the person is expected to spend working.

In developed countries, assuming a gross domestic product per person of about 28.575 euros, the value of a statistical life according to the LQI would be about 1-4 million euros depending on the discount rate (see [24: 72]). The fact that the LQI leads to higher VoSL-estimates than macro-economic valuation is due to the fact that in the LQI-method zero utility is attributed to life time spent working. Thus, more life years have to be saved to obtain a similar increase in utility.

6 COMPARISON OF VOSL-ESTIMATES

Comparing different VoSL-estimates that were obtained by either revealed or stated preference methods can be difficult. The initial risk level is important as the marginal willingness to pay is generally assumed to decrease with lower risk levels [4]. Only when the demand curve is horizontal is willingness to pay independent of the initial risk level and only then is a proper comparison of WTPs possible. At low risk levels, this may be the case [4]. The hazard type and context are important as risk perception influences the willingness to pay for risk reduction. Only VoSL-estimates based on non-behavioural methods are independent of initial risk level, hazard type and context . Non-behavioural valuations can thus more easily be generalized and compared.

Non-behavioural valuations are in the order of 1-4 million euros. As shown, macro-economic valuation yields a VoSL of about 0.5 million euros in developed countries. The life quality index methodology will result in values of 1-4 million euros. Behavioural valuation methods can produce much higher VoSL-estimates. Consider for example a CSXY-value of $1.2.10^6$ 1993-US dollars for a ban on chlorobenzilate pesticide on citrus [19: 377] indicating a VoSL of about 91 million 1993-US dollars. However, the VoSL-estimates obtained by these methods vary over several orders of magnitude, even within hazard categories, providing a poor basis for a robust cost-benefit analysis. Using a standard VoSL for industrial safety based on behavioural valuation seems problematic because of the contextual factors that determine people's willingness to pay for risk reduction measures.

Behavioural methods produce VoSL-estimates that are influenced by risk perception, unlike non-behavioural valuation methods. Considerations about the acceptability of risks from an individual, societal and economic perspective are all reflected in the same VoSL-estimate. In industrial safety regulation, risk criteria are in use that consider industrial risks from an individual and societal perspective. When separate individual and societal risk criteria have already been put in place, one could consider it inappropriate to adopt this methodology to obtain VoSL-estimates: perspectives would blur and the added value of adopting a separate economic perspective would be low. An overview of the values of a statistical life according to the different valuation methodologies is presented in Table 1 for developed, industrialised countries.

Valuation methodology		*order of magnitude of VoSL (euros)*
behavioural valuation	*stated preference*	*no estimate*
	revealed preference	*0-10^{10}*
non-behavioural valuation	*macro-economic valuation*	*$0{,}5.10^6$*
	life quality index	*$1\text{-}4.10^6$*

Table 1 Valuations of loss of life in industrial safety

7 ECONOMIC OPTIMIZATION OR SOCIETAL COST BENEFIT ANALYSIS

Whether explicitly valuing loss of life will influence decision making depends strongly on the type of problem that is evaluated. In a societal cost benefit analysis for hazardous activities as a whole, valuing loss of life is unlikely to influence the net financial balance because the probability of harm to humans is generally low. In economic optimizations of risk control measures, valuing loss of life could however influence the optimal investments in safety.

Consider a chemical installation in the vicinity of a residential area. Assume that the expected value of the number of statistical lives lost due to accidents at the chemical plant is 10^{-3} per year. Considering the individual and societal risk criteria in the Netherlands, this is quite a high value. If the installation generates 1 million euros per year, the cost associated with one death would have to be in excess of 1 billion euros if the expected value of benefits is to become negative and the activity banned on economic grounds. Material losses and other intangible losses are likely to be correlated with loss of life. Still, a value in excess of 1 billion euros for all damages associated with the loss of 1 person indicates an extremely high value of a statistical life. The safety standards in the process industry as well as risk criteria have resulted in such low probabilities of harm to humans that loss of life has become a marginal cost item in the net financial balance for industrial activities as a whole.

Now consider the investment in a risk reduction measure. If an accident were to result in the loss of one statistical life and 1 million euros in damages, valuing loss of life at 1 million euros would strongly influence the optimal investment in risk reduction as potential damages are then doubled. Without valuing loss of life, a measure that could reduce the probability of an accident from 10^{-3} to 10^{-6} per year should cost less than 999 euros. When loss of life is valued in monetary terms, that measure should cost less than 1998 euros.

8 DISCUSSION AND CONCLUSIONS

Two distinct types of valuation methodologies have been discussed: behavioural and non-behavioural approaches. The valuation methodology has considerable influence on the value assigned to loss of life. None of the valuation methods is without ethical or methodological problems.

Only behavioural approaches provide measures of social preference. Applying these approaches for making investment decisions in the context of industrial safety regulation is however troublesome. Stated preference methods are time consuming and have some methodological difficulties. Revealed preference methods for industrial safety value loss of life based on past investments in risk reduction. However, statistics of the past provide little guidance for making new investment decisions since the values of saving a statistical life vary widely within and between hazard categories.

Non-behavioural valuation methods do not elicit social preferences; rather they assign an economic value to loss of life based on productivity. Because these valuations are based on rather stable macroeconomic indicators they lead to stable reference values for loss of life. In developed countries, macroeconomic valuation yields a value of a statistical life of about 0.5 million euros and the life quality index a value of about 1-4 million euros.

With these valuations, valuing loss of life in monetary terms will generally not be important in a CBA that is about a comparison of the costs and benefits of an entire activity (e.g. a CBA for a chemical plant in a populated area) because the probability of death is already very limited due to stringent risk regulations. However, for optimizations of investments in risk reduction (e.g. optimization of dike height) valuing loss of life can sometimes be important for the outcome.

It is suggested not to value loss of life in monetary terms in CBAs for industrial activities as a whole, because loss of life will otherwise be a marginal item in the decision-making process. For such CBAs, it is proposed to list potential loss of life separately as a PM-item together with all other intangible losses. These intangible losses then have to be weighed politically against the net financial balance. This method is in line with the recommendations of the guide for societal-cost benefit analysis on infrastructural projects that was developed for the Dutch government [26].

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