This paper is a non-peer reviewed work

Floods and Water Management in Chiang Mai and the Upper Ping catchment, Northern Thailand

Cassian Pirard(1)*

(1) Dr Artima Medical Clinic, International Health Services, Maehia, Chiang Mai, Thailand
* Corresponding author: cassian.pf.pirard@gmail.com

Abstract

The city of Chiang Mai, Northern Thailand has been subject to regular major floods in the past couple of decades. In this review, we provide some background information on the hydrology of Upper Ping river catchment, the hydrogeology of the Chiang Mai – Lamphun basin, historical records of hydrological events in the area and more recent depictions of major floods. In the second part of this review, a development on the potential causes of floods, the issues of water management in the catchment and the advances in flood modeling and projections on future climate in the upper Ping and its influence on the waterways is also explored.

Introduction

This document is an attempt to synthesize information, knowledge and thoughts on water management in Chiang Mai and the Upper Ping River using published scientific sources of information and official data produced by Thai governmental or royal institutions. It covers general information about the Ping river system and aquifers around Chiang Mai but also specific concerns and explanation regarding floods, droughts, aqueous pollution and exploitation and future trends regarding the water system in Chiang Mai province.

It is the result of a similar train of thought than a previous publication on air pollution in the Northern Thailand (Pirard & Charoenpanwutikul, 2023) where the amount of mis- and dis-information available for public consumption regarding concerns about natural disasters (i.e. floods, droughts, burning season, seismic activity) through various media provides very foggy, uninformed statements and contradictory views about these phenomena. A less biased and better understanding of these natural processes can be obtained from scientific publications which, with some exceptions, is generally consistent throughout the specialised literature. It provides an infinitely more precise, defined and accurate view of the real issues without being sidetracked by ‘fashionable’ or dumbed-down concepts, appealing and anxiogenic commentaries and socially-charged interpretations.

Table of Contents

1. Hydrology of the Ping catchment

1.1. General description of the catchment

The Mae Ping River is a 740 km long river in Northern Thailand flowing North to South from the mountains near the Burmese border to the Central Plains of Thailand. Boundaries of the basin are to the West, the Salween river basin to which the Pai river, west of Chiang Mai, belongs to; to the North is the Mekong basin while the eastern boundary is the Yom & Nan rivers that join the Ping in the Central Plains to become Chao Phraya river (Fig. 1). The catchment covers around 34000 km^2 (Chaipimonplin, 2010; Bidorn *et al.*, 2015; Rangsiwanichping & Melesee, 2022; Chapagain *et al.*, 2025), similar to the size of a small European country, Taiwan, Maryland, etc. The Ping river passes through some important towns such as Chiang Mai, Lamphun, Tak and Kamphaeng Phet before meeting the Nan River in Nakhon Sawan and renamed into Chao Phraya to flow through Bangkok and the sea.

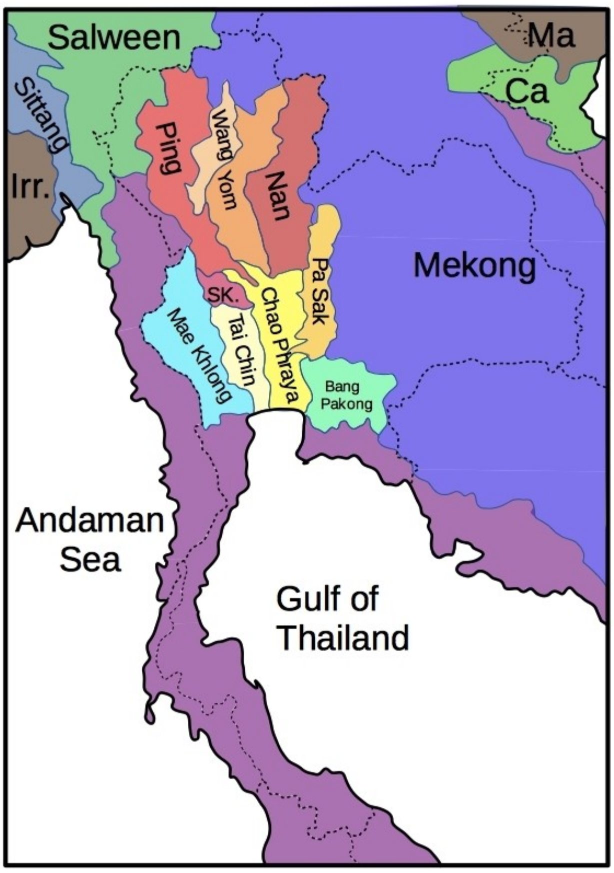


Figure 1. Schematic map of the main river basins in the central part of continental South-East Asia. Unlabelled areas are coastal catchments. Dotted lines are country boundaries.

The Ping river represents 22% of the whole Chao Phraya catchment and contributes to 24% of the runoff with an annual average flow of 62 m^3/s (Reda *et al.*, 2013; Bidorn *et al.*, 2016; Rangsiwanichpong & Melesse, 2022) with a slope varying mostly between 1:1600 and 1:2300 (Mapiam & Sriwongsitanon, 2009; Bidorn *et al.*, 2016; Chapagain *et al.*, 2025). The entire catchment is covered by 46.5% forest, 31.2% agricultural land and 12.6% of paddy fields (Chaipimonplin, 2010) (Fig. 39).

In the literature, the Ping river is divided into the Upper Ping from headwaters to the confluence of Wang river, north of Tak or, since the building of the Bhumibol dam, to Doi Tao lake; while the lower Ping is defined between Bhumibol dam or Wang river confluence and the Nan confluence in Nakhon Sawan. With the significant influence of Bhumibol reservoir (see 6.1.1), the term middle Ping is sometimes used for the section between Doi Tao lake and the dam due to its flooded valley characteristics.

The Upper Ping river, defined in the rest of this document as the section down to Doi Tao Lake, covers an area of 23570 km^2 (Sriwongsitanon, 2010; Chaipimonplin, 2010; Komsai *et al.*, 2016) in a catchment covered at 66% by forest, 26% by agricultural land and 4% urban (Chapagain *et al.*, 2025). The average annual runoff into Doi Tao lake is 6812 Mm^3 (Mapiam & Sriwongsitanon, 2009). The basin is divided into 15 to 62 sub-catchments depending on how much details are necessary for various studies (Fig. 2). The main tributary rivers (and length) are Mae Ping (283 km), Mae Taeng (155 km), Mae Rim (56 km), Mae Ngat (82 km), Mae Kuang (115 km), Mae Wang (116 km), Mae Tha (78 km) and Mae Li (212 km) to which can be added the Mae Chaem river (170 km) flowing directly into Doi Tao lake (Tansar *et al.*, 2021; Triritthwittaya *et al.*, 2022).

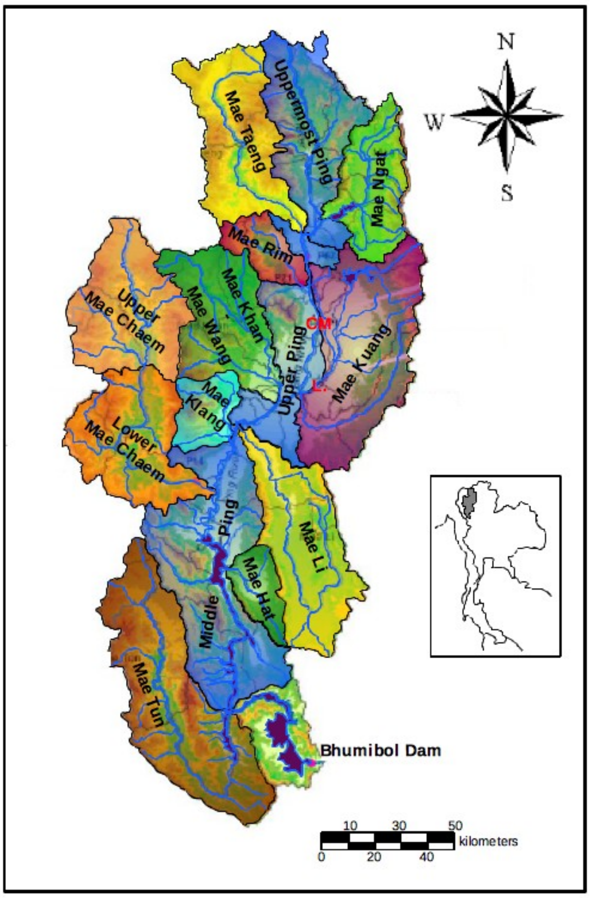


Figure 2. Map of the sub-catchments of the Upper & Middle Ping river. Rivers are in blue, cities in red (CM: Chiang Mai; L: Lamphun) and water reservoirs in purple. Various colours are given for each sub-catchment overlayed on a topographical map.

The Ping river takes its source 190 km upstream of Chiang Mai, near the Burmese border, in Doi Thuai, a southern extent massif of the Daen Lao range which serves as a dividing range between Salween and Mekong basins. The headwaters are mostly streams in gravel beds bounded by steep sloped lands along mountain ridges. Tributaries in some places have deeply incised into the mountain ranges creating gorges such as Ob Luang and Ob Khan along the Mae Chaem river. Eventually, major creeks (Upper Ping, Mae Ngat, Mae Rim and Mae Taeng) merge to form the Upper Ping as it is seen flowing through Chiang Mai (Jarungrattanapong & Manasboonphempool, 2011). At that stage, the catchment is 6350 km^2 (Wood & Ziegler, 2007, 2008; Lim & Boochabun, 2012; Boonrawd & Jothityangkoon, 2015; Itayama *et al.*, 2015) where 80% of the catchment is a steep terrain with elevation higher than 500m (Chaipimonplin, 2010).

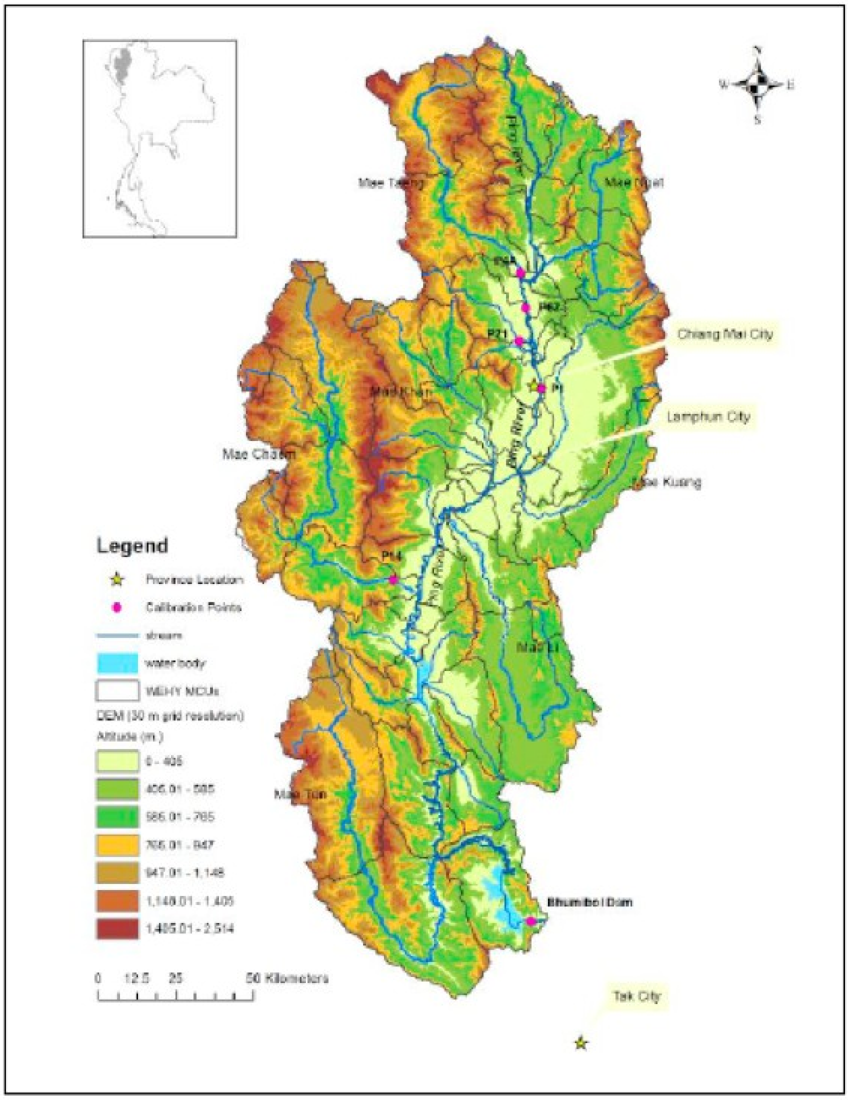
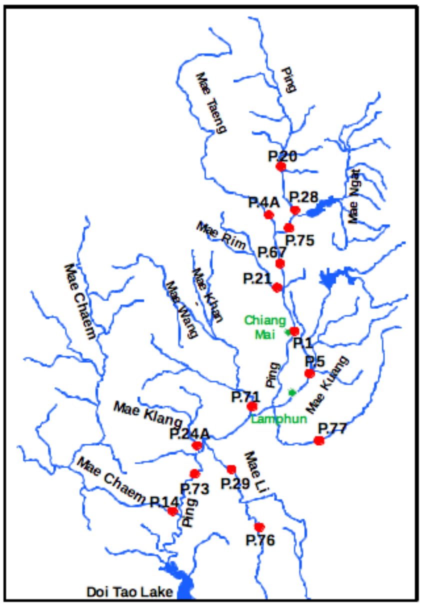


Figure 3. Topography of the Upper Ping catchment with main mountain ranges and the Chiang Mai-Lamphun (CML) basin clearly visible in light green (Wuthiwongyothing *et al.*, 2017)

However, after the confluence of these rivers, the topographical situation changes drastically as the Ping river enters the Chiang Mai-Lamphun (CML) basin, an area 25 km wide in the central part made of a flat rising plain ranging from 280 to 360 m over ~140 km and escarpments of 1685m (west) and 1025m (east) on both sides (Margane & Tatong, 1999) (Fig. 3). In this plain-like section, the slope of the Ping river goes from 0.0087 to 0.0044 (Wood & Ziegler, 2007, 2008; Bonrawd & Jothityangkoon, 2015; Pholkern *et al.*, 2015). The tributaries that join the Upppermost Ping and the Ping river in the basin are monitored through a network of around 20 gauge stations carefully positioned to estimate the output of each sub-catchment into the Ping river (Fig. 4).

The average flow velocity of the Ping river is 49.5 km/day (0.5 m/s) (Boonrawd & Jothityangkoon, 2018) but it remains an average since 55.5% of the basin lies above 500 m with significant slopes and considerably faster flow rates (Laonamsai *et al.*, 2023). The annual average velocity in the Upper Ping is around 1.2 m/s with base flow variations between 1.08 and 0.04 m/s depending on the season (Pholkern *et al.*, 2015). During floods, flow velocity can be slightly higher and it generally takes a lot less than 48 hours for the first signs of a flood front to reach Chiang Mai (Lim & Boochabun, 2012) (Fig. 18). In terms of volume, the average annual flow is 26 m^3/s (Wood & Ziegler, 2007, 2008) to around 60 m^3/s as the average rainy season base flow (Chaipimonplin, 2010; Pholkern *et al.*, 2015) and dry season flows at 1.8 to 3.5 m^3/s (RID database), around twice lower than the minimum annual flow of 8 m^3/s (RID database). The average annual peak flow on the other hand, is around 400 m^3/s (Lim & Boochabun, 2012) with records peak flow around twice higher (see 4.1.). The value of maximum and minimum annual base flows are based on the season and its characteristics. Annual peak flow and minimum flow have correlation with rainfall averages (annual & seasonal) and minimum flow also shows a correlation with the previous monsoon season rainfall (Lim *et al.*, 2012).



List of river level stations in the Upper Ping

Station	Location	Catchment area
P.20	Uppermost Ping	1339 km^2
P.28	Mae Ngat	1267 km^2
P.4A	Mae Taeng	1939 km^2
P.75	Upper Ping [2]	771 km^2
P.67	Upper Ping [3]	498 km^2
P.21	Mae Rim	510 km^2
P.1	Upper Ping [CM]	1112 km^2
P.5	Mae Kuang [L.]	1777 km^2
P.77	Mae Tha	544 km^2
P.71	Mae Ngan	1727 km^2
P.76	Upper Mae Li	1543 km^2
P.29	Mae Li	1966 km^2
P.24A	Mae Klang	454 km^2
P.73	Middle Ping	2242 km^2
P.14	Mae Chaem	3853 km^2

Figure. 4. List and position of river level gauge stations in the Upper Ping catchment.

Several significant reservoirs are also present in the Ping catchment. The Bhumibol reservoir which extend upstream to the Doi Tao lake, has a volume of 13462 Mm^3 and can absorb most peak outflow from the Ping river. Mae Kuang reservoir (263 Mm^3) and Mae Ngat reservoir (265 Mm^3) lies upstream of Chiang Mai in their respective sub-catchments and play a significant role in maintaining base flow during the dry season and flood management (Mapiam & Sriwongsitanon, 2009). In addition to these very large reservoirs, around 50 smaller artificial lakes with volume between 0.05 Mm^3 and 20 Mm^3 lies in the upper Ping basin (see table below).

1.2. Description of Ping basin

The uppermost Ping is mostly flowing through sedimentary, volcanoclastics and metasedimentary perm-carboniferous rocks then enters the Chiang Mai – Lamphun (CML) Basin. Similar rocks to the uppermost Ping are still found on the eastern margin of the basin and a variety of upper-Paleozoic & Mesozoic granitoids and lower to middle Paleozoic metasediments on the western margin (Fig. 5).

The CML basin itself is an intermontane basin formed in the Late Cretaceous – Early Tertiary and bounded by N-S extensional faults where the basin itself is a sediment-filled graben system (Margane & Tatong, 1999). The continuous down-faulting since the Late Cretaceous (Wattananikorn *et al.*, 1995; Chaimanee, 1997) created a subsidence filled with 2000 meters of sediments. In recent times, the areas with the highest subsidence have higher accumulation of Quaternary sand and gravel while stable blocks have slope-wash colluvial sediments of clays and silts (Margane & Tatong, 1999).

The Ping river passes in recent times in the middle of the basin as a 40 to 130 meters naturally braided river which is currently restricted to a single alluvial channel of low sinuosity with a sandy riverbed and leveed banks 3 to 4 meters above the channel bed and often used as narrow roadways (Laonamsai *et al.*, 2023). Right outside this basin, river valleys are deeply weathered old terraces with 1 to 10 meters of saprolite and a few meters of argilic soil horizons and eventually a few tens of centimeters of dark brown loamy soil. At the bottom of those valleys, the narrow floodplain is mostly paddies made of clayey and gleyed soils (Wood & Ziegler, 2008).

List of reservoirs in the Upper & Middle Ping catchment

Name	Surface (m^2)	Estimated Volume (m^3)	Sub-catchment
Mae Khi	45000	80000	Mae Rim
Huai Rai	24000	60000	Mae Rim
Huai Mae Ka	75000	700000	Mae Taeng
Mae Taeng Dam	90000	110000	Mae Taeng
Huai Chomphu	50000	60000	Mae Taeng
Huai Bong	70000	220000	Mae Taeng
Mae Phaen	240000	2000000	Mae Ngat
Huai Ngu	75000	250000	Mae Ngat
Huai Takhian	36000	65000	Mae Ngat
Ang Maew	81000	300000	Mae Ngat
Mae Kon	250000	2500000	Mae Ngat
Ang Hongtraay	81000	400000	Mae Ngat
Mae Ngat Somboon Chon	16000000	265000000	Mae Ngat
Ban Na Pak	90000	330000	Mae Ngat
Huai Kang	75000	200000	Mae Ngat
Huai Kuk	70650	100000	Mae Ngat
Ang Mae Hot	75000	200000	Mae Ngat
Huai Mae Prachum	250000	2000000	Mae Ngat
Pa Sak Ngam	37500	120000	Mae Kuang
Mae Kuang Udom Thara	11800000	263000000	Mae Kuang
Huai Cho	102000	450000	Mae Kuang
Huai Kiang	28000	80000	Mae Kuang
Huai Sak	72000	270000	Mae Kuang
Huai Hong Khrai W	88000	220000	Mae Kuang
Huai Hong Krai E	196250	800000	Mae Kuang
Sahakorn	140000	420000	Mae Kuang
Huai Bok	140000	700000	Mae Kuang
Huai Mae On	525000	3000000	Mae Kuang
Huai Lan	522500	3500000	Mae Kuang
Mae Pha Haen	285000	1200000	Mae Kuang
Mae Thi	288000	800000	Mae Kuang
Mae Tip	552500	3000000	Mae Kuang
Mae San	300000	1500000	Mae Kuang
Mae Yen	180000	1300000	Mae Ping
Huai Tueng Thao	400000	1800000	Mae Ping
Navamin	150000	1000000	Mae Ping
Angkaew	64000	400000	Mae Ping
Pong Cho	400000	18000000	Mae Wang
Huai Manao	315000	1500000	Mae Wang
Mae Wang San	390000	1200000	Mae Li
Mae Moi	720000	5000000	Mae Li
Mae Lao Yai	192500	770000	Mae Li
Pa Sang On	405000	4500000	Mae Li
Mae Ei Hi	225000	1800000	Mae Li
Mae Tuen	297500	1800000	Mae Li
Mae Tub	3850000	3850000	Mae Li
Mae Hat	180000	720000	Mae Li
Bhumibol-Doi Tao Reservoir	300000000	13462000000	Mae Ping

The floodplain of the CML basin is made of Quaternary sediments, separated from the river by 0.5 to 1 meter high levees (Wood & Ziegler, 2007, 2008) that can be up to 5 to 12 m above the river bed (Lim & Boochabun, 2012; Pholkem *et al.*, 2015). The floodplain is around 3 km wide and mostly made of silty clay typically found in rice paddies as well as some sand sheets of past Holocene natural levees.

The terraces that rest a few meters to several tens of meters above the floodplain were deposited during the Pleistocene. During the humid conditions of interglacial periods, pebbly beds would be formed while the drier and cooler climatic fluctuations associated with glacial episodes deposited finer sediments, typically on top of the terraces through sub-aerial erosion. Further south, those fluviatile Tertiary and early-middle Pleistocene terraces show evidence of tectonic subsidence and a transition from intermontane to standard alluvial plain while CML still remain entirely intermontane. Neo-tectonic activity on the Mae Ping fault also show recent effects with the presence of unpaired terraces (Bhongaraya *et al.*, 2009).

Low terraces are rarely preserved on the surface due to frequent flooding and are up to 5 m above the floodplain. Their age is likely Late Pleistocene. Middle terraces are 5 to 20 m above the floodplain and made of gravel beds partly saprolitised and laterised over 25 cm with an approximate age of middle Pleistocene. The high terraces are formed earlier and occur along the mountain ranges with rare outcrops within the basin, where down faulting can cause a local uplift (Margane & Tatong, 1999). High terraces are around 50 to 70 m above the floodplain and made of hills of laterised gravel beds of early Pleistocene or older.

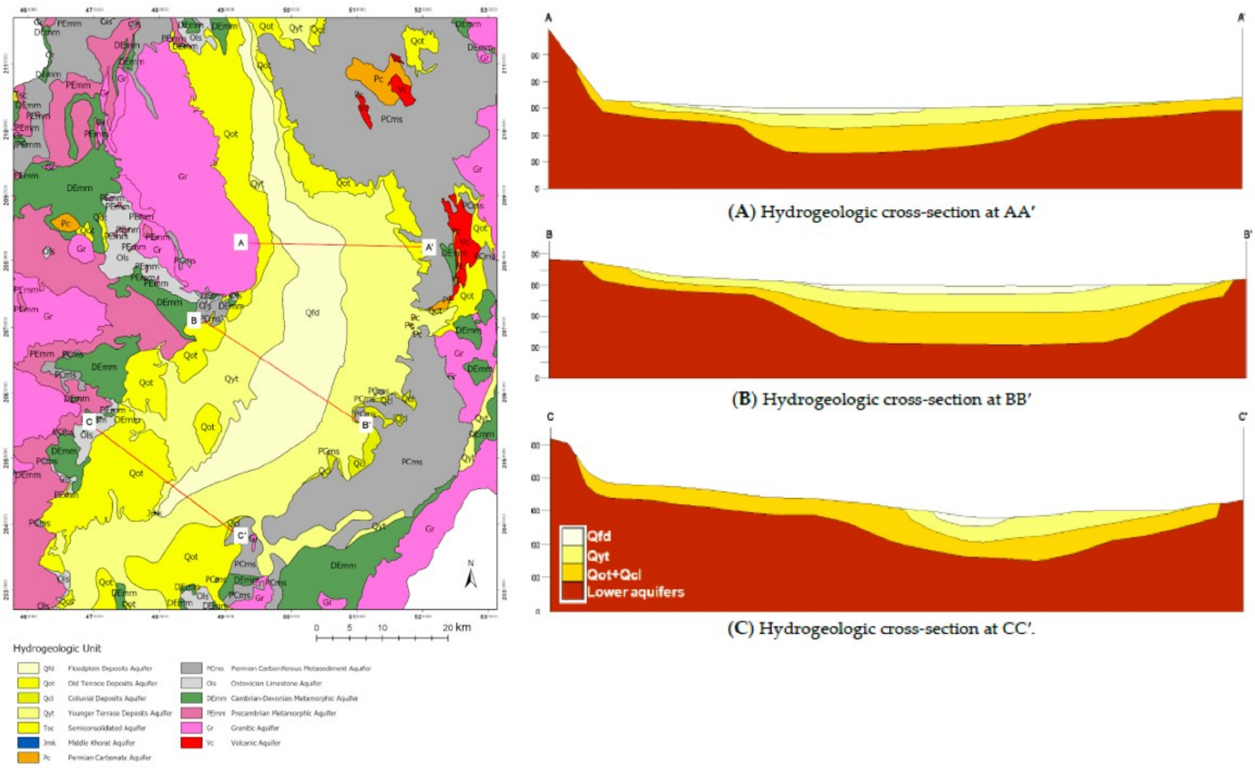


Figure 5. Left: Geological map of the Chiang Mai – Lamphun (CML) Basin and direct surrounding. The yellow area are Quaternary and some Tertiary sediments on the edge of the basin. Right: Some hydrogeological cross-section through the basin (modified from Taweelarp et al., 2021).

Alluvial fans are sedimentary deposits from tributaries arriving from the hills directly into the basin. Mae Kuang is a typical example with interfingering of gravel & sand beds with clay & silt units indicating the rapid changes in the course of such streams and rivers (Margane & Tatong, 1999). Alluvial fans covers Tertiary piedmont plains, old and recent terraces, the floodplain and some recent point and sand bars (Bhongaraya *et al.*, 2009). Such alluvial benches can be 5 to 10 m above the floodplain and covered with fruit orchards, paddy rice fields and urbanized zones (Wood & Ziegler, 2007, 2008).

1.3. Description of Ping river waters

1.3.1. Sediment load & turbidity

Like most rivers in tropical countries, the Ping has a constant high loading of sediment due to the intense weathering. Sediment concentration during the rainy season is 500 mg/l (for comparison, European rivers rarely reach 50 mg/l of suspended sediment load), which provides a high potential of silt deposition especially when the hydraulic conductivity is lowered as it occurs in the CML basin (Pholkern *et al.*, 2015). At the peak of the 2005 flood at Nawarat Bridge, the suspended sediment concentration of Ping river was measured at 1020 mg/l with models showing that 800-1500 mg/l are likely common values in that stretch of river during flooding (Wood & Ziegler, 2007). The long term variations of sediment load in the Ping river are controlled by the natural profile of the river but also external factors such as deforestation, agriculture, population pressure, development of irrigation, dams, reservoirs and climate change (Bidorn *et al.*, 2016).

Turbidity is closely linked to sediment load but differs in the way it is measured. While the uppermost Ping river has relatively low turbidity (Leelahakrienkrai & Peerapompisal, 2010), it increases significantly after Mae Rim river confluence and then slowly decreases downstream. It also varies significantly over the years, notably reaching peaks in 1997 and 2007 as a consequence of upstream dredging (Itayama *et al.*, 2015). Medium levels of turbidity are not abnormal and as it is the case for the nearby Mekong, the flora and fauna of the Ping river is likely adapted to these murky conditions (Itayama *et al.*, 2015).

1.3.2 Water quality

The water quality of the Ping river is good in the uppermost part of the catchment where it is mostly surrounded by deciduous forests. As it flows downstream, the alkalinity increases due to the limestone basement while orchards create minimal pollution (Leelahakrienkrai & Peerapompisal, 2010). However, in the larger valleys, agriculture, some small scale industries and manufacturing plants, urban activities and some minor mining operations increase the pollution in the Upper Ping (Hui Yian Lee *et al.*, 2024). Significant changes in land use in the past decades have also provided various new inputs in agrochemicals, nutrients and toxic pollutants as well as disturbance pressure on the ecosystem (Itayama *et al.*, 2015). However, levels are fairly low in common pollutants with 0.1±0.05 F mg/l, 2 to 8 Cl mg/l, 1.5±1 NO_3^- mg/l and 5.5±1 $SO_4^=$ mg/l before entering the CML Basin (Ogata *et al.*, 2020).

Once in Chiang Mai, urban pollution significantly increases, partly due to an insufficient waste water treatment system and a poor management and maintenance of septic tanks.
The centralized waste water treatment plant of the city can only process around 50% of the total population output while most (80% on national average) use a septic tank with the septic sludge collected and transferred to the waste water treatment plant episodically (Hui Yian Lee *et al.*, 2024). In addition, waste water treatment plants have only a basic processing limited to flocculation and

settling which does not remove all essential pollutants and effluents have contaminants transferred to the river and reservoir systems.

A significant amount of grey water also makes its way to the waterways resulting in some canals and ditches being the most polluted water bodies in Chiang Mai (Hui Yian Lee *et al.*, 2024). The Mae Kha canal flowing through the inner city for example, has an average annual flow rate of 0.7 m^3/s while the maximum rate of the sewage treatment plant is 0.55 m^3/s, leaving 0.15 m^3/s of untreated urban drainage (Itayama *et al.*, 2015) and possibly a lot more during the rainy season. With the rise of the water table during the rainy season and abundant surface flow, the situation is exacerbated with further mobilization of human waste, improperly discarded industrial waste and general use polluted water. This is particularly exemplified by the presence of specific tracers such as pharmaceuticals (diabetes drugs, pain killers, anti-histamines) and industrial waste (sugar substitutes, caffeine, surfactants, detergents) present in grey water releases ending up in the Ping river (Hui Yian Lee *et al.*, 2024). Eventually, this urban pollution concentration decreases downstream towards Doi Tao Lake.

Seasonality is low in contamination from urban sources (other than the relationship with rainfall) but varies a bit more in rural and remote areas where pesticides and agro-chemicals on the surface can be mobilised during heavy rainfall shortly after application time (Hui Yian Lee *et al.*, 2024). Variations over 3 decades of records of water quality by the Pollution Control Department (PCD) show that the upper weir pool of Chiang Mai city (upstream of Tha Wang Tan) has improved but the water quality after the output of Mae Kha canal had deteriorated in 2015 (Itayama *et al.*, 2015) despite an improvement following a closer management of the Mae Kha canal in 2003 that has reduced waste water, lowered ammonia and phosphorus content and improved oxygen levels (Leelahakrienkrai & Peerapompisal, 2010). The recent upgrades of the canal are mostly esthetic and physical and have little effect on pollutants.

While the Ping passes through Chiang Mai, water chemistry is slightly modified with anions (F, Cl, NO_2, NO_3, SO_4) at relatively low concentration in the upstream area but increasing significantly closer to the city due to residential areas and agriculture. Fluorine remains mostly below 1 mg/l, Chlorine below 20 mg/l, NO_3^- below 5 mg/l and $SO_4^=$ below 10 mg/l while all heavy metals (Cu, Ni, Mn, Zn, Cd, Cr, Hg) are below detection limit and high concentration contaminant such as Mg and Ca are of natural sources as well as Na, Si, S and K probably mobilised due to accelerated erosion (Ogata *et al.*, 2020).

Another estimation of the cleanliness of Ping river water is the Water Quality Index (WQI), the equivalent for water bodies of the AQI for air pollution (Pirard & Charoenpanwutikul, 2023). Input variables are dissolved oxygen, biological oxygen demand, total coliform bacteria, fecal coliform bacteria and ammonia-nitrogen contents making the WQI a scale going from 0 (very poor) to 100 (very good) (Suphawan & Chaisee, 2021). The Ping river has an WQI average of 58 and median of 70 and varies between 41 and 89. Chiang Mai sees its lowest values around Mahidol Road bridge (61.47±7.36) and as low as 41 near Wang Sing Khum Bridge (Suphawan & Chaisee, 2021). From a biological point of view, the upper Ping is oligo-mesotrophic (clean to moderate), further downstream, it is mostly mesotrophic (moderately clean) (Leelahakrienkrai & Peerapompisal, 2010) and anthropogenic eutrophisation is not a major ecological disturbance (Itayama *et al.*, 2015).

2. Meteorology in the upper Ping catchment

Northern Thailand climate is a typical tropical savanna (Köppen classification Aw) climate of broadly hot weather with marked dry and wet season, applicable for most of Thailand. The annual weather is characterised by 3 main seasons: the rainy season from May to Mid-October has a South-West Monsoon bringing moisture from the Indian Ocean; the cold season is from Mid-October to Mid February with a North-East monsoon bringing some moisture from the South China Sea and the hot season from mid-February to Mid-May in pre-monsoon conditions (Boochabun *et al.*, 2004; Singhrattana *et al.*, 2005; Chaipimonplin *et al.*, 2011; Reda *et al.*, 2012, 2013) (Fig. 6). The regional weather is heavily influenced by the Indian Monsoon due to the position of the Hadley cell over Indochina and the South China Sea (Kripalani & Kulkarni, 1997). The surface temperature of the Pacific Ocean is also known to provide significant trends (particularly in the last 3 decades) with El Niño characterised by low monsoon rainfall compared to La Niña (Rasmusson & Carpenter, 1983; Ropelewski & Halpert, 1987; Kripalani & Kulkarni, 1997). The role of El Niño is to shift the descending limb of the Walker cell over Thailand, reducing convection and precipitation due to the Indian monsoon through (Singhrattana *et al.*, 2005).

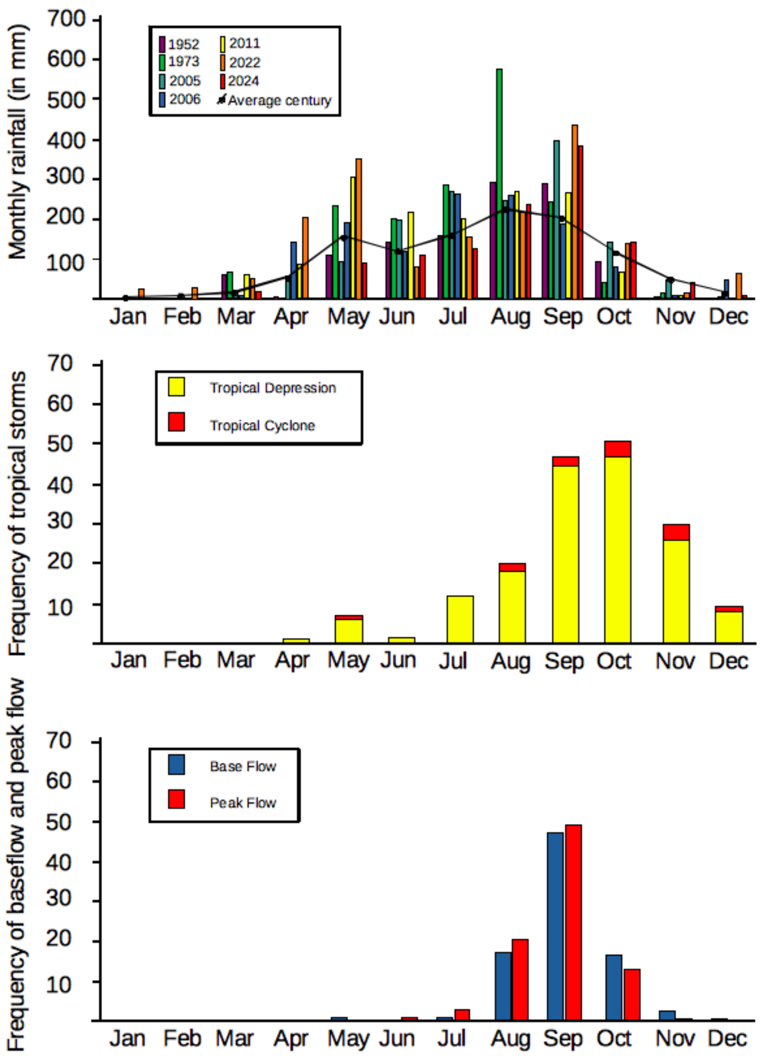


Figure 6. Monthly average of rainfall and frequency of tropical storms in the past few decades and the frequency of baseflow and peak flow associated with flooding events (modified from Lim & Boochabun, 2012)

In the Upper Ping basin, average temperatures range between 20.7 and 34.0ºC with an annual mean of 27ºC (Reda *et al.*, 2013). Temperatures reaching the upper thirties are not uncommon in the hottest part of the summer season (April-May) while the cold season can occasionally be below 15ºC in the CML basin. Historical extremes are 42.5ºC in Chiang Mai in May 2016 while the coldest ever recorded is -5ºC on Doi Inthanon in 2017 and only 3.8ºC in Chiang Mai in December 1999.

The average annual rainfall over the region is around 1100 mm/yr. It varies from 800 mm/yr long term average for the plains in the CML basin to values exceeding 1500 mm per year recorded on mountain ranges (Margane & Tatong, 1999; Rodratana & Pamsa-nga, 2008; Chaipimonplin, 2010; Chaito *et al.*, 2021). This is partly due to the elevation effect that add 0.5 mm of rain for each 100 m of altitude (Vongtanaboon *et al.*, 2008) but also orographical rainfall enhancement during storm events (Lim & Boochabun, 2012) (Fig. 7). Most (85 to 90%) of the rainfall occurs during the rainy season between May and September with the wettest month in August or September (Reda *et al.*, 2013; Bidorn *et al.*, 2016; Cheevaprasert *et al.*, 2020; Weesakul *et al.*, 2022) (Fig. 6).

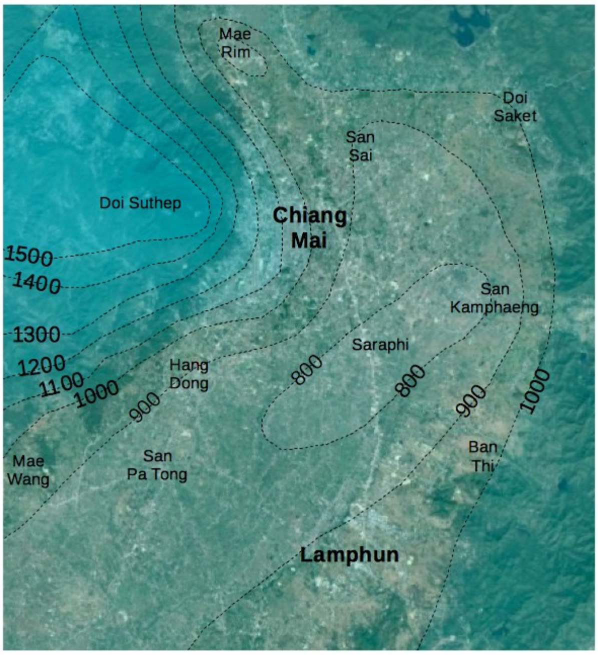


Figure 7. Annual isohyets for the region surrounding Chiang Mai clearly showing the effect that mountains (particularly Doi Suthep here) have on annual rainfall (1988-1997) averages (modified from Margane & Tatong, 1999).

Rainfall in the Upper Ping basin is recorded continuously for more than a century in a handful of stations, providing valuable information for long term trends and variability. Despite having an insufficient number of rain gauges or an uneven distribution in the basin, limiting the accuracy of total rainfall over the catchment, records show that the monthly rainfall is highly dependent on summer thunderstorms in April and May, the increasing influence of the South West Monsoon in August and September and the passage of tropical depressions from the South China Sea (Weesakul *et al.*, 2022) (Fig. 6). As a result, while locations such as Samoeng (Chiang Mai) or Mae Tha (Lamphun) have a long-term average rainy season of 700 to 800 mm/yr, minimum annual rainfall can be as low as 300 mm/yr and maximum of almost 2000 mm/yr have been recorded in the past. The modeling of this long term variability gives a rainfall return period of 1 year to be below average and 2 years for average, 10 years with 150% rainfall, 20 years for 180% and 100 years for

200% (Chaito *et al.*, 2021) (Fig. 8). Long term yearly averages also show that the number of wet spells (>0.3 mm) of 2 to 4 days duration occur 16x per year; durations of 5 to 7 days occur 3x per year and there is on average only one occurrence per year of rainy days lasting for more than a week (Cheevaprasert *et al.*, 2020).

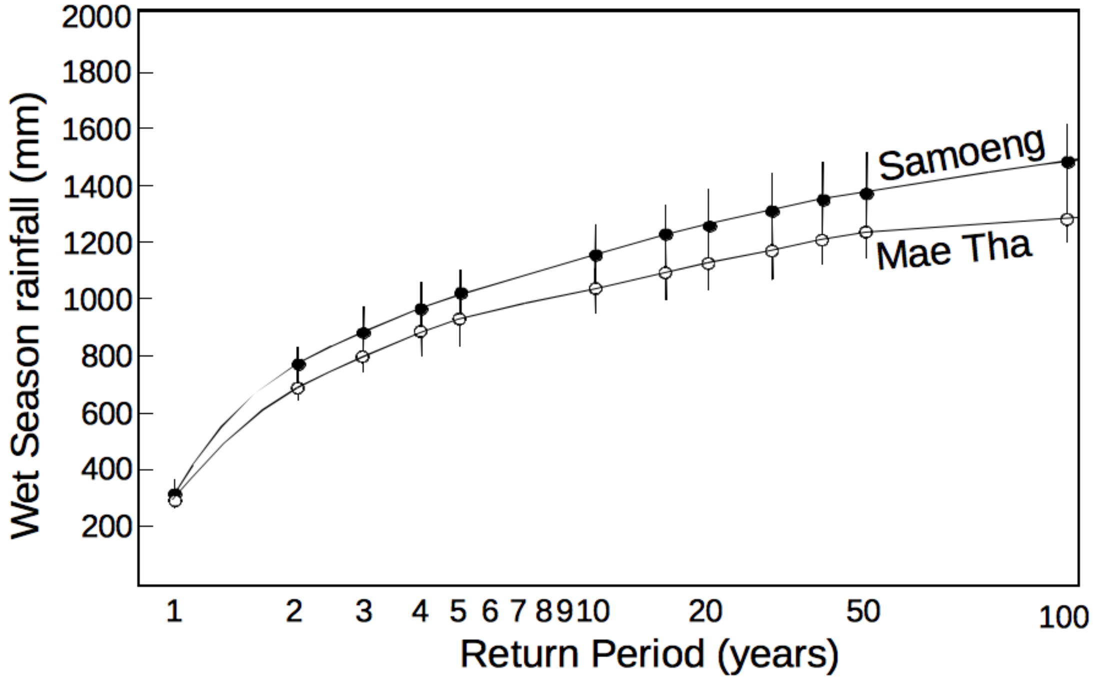


Figure 8. Recurrence rate of annual average rainfall in Samoeng and Mae Tha with associated error bars (data from Chaito *et al.*, 2021)

In the last few decades, satellite imagery has provided significant support for regional rainfall estimates with correlation factor of 0.8 to 0.98 with rainfall gauges. There is however a significant underestimation of rainfall in mountainous terrain (Boonchum *et al.*, 2020). Finally, weather radar in Chiang Rai, Lamphun and Mae Hong Son established a complete coverage of the Ping catchment and can be combined with other methods of rainfall monitoring (Chaipimonplin, 2010) (Fig. 47).

3. Hydrogeology in the Chiang Mai – Lamphun basin

3.1. Aquifers

The Chiang Mai – Lamphun (CML) Basin is a 70 x 45 km^2 cuvette of structural origin containing in excess of 1200 meters of Tertiary fluviatile sediments deposited uncomformably upon Paleozoic rocks (Lerdthusnee *et al.*, 1981; Taweelarp *et al.*, 2021). Various sedimentary and hydrogeological units are described in the characterization of the basin extending from the central alluvial floodplain to the terraces on the edge of the basin. Old hydrogeological models suggested that the aquifer system under the CML Basin is controlled by the distribution of paleoterraces (Chuamthisong, 1971; Buapeng *et al.*, 1995) and although it might be partly confirmed for the middle Ping hydrogeology, there is no strong evidence that it is the case in the CML Basin. There is however several distinct sedimentation domains within the basin that would create hydrogeological units down to 200 meters (Margane & Tatong, 1999) (Fig. 9).

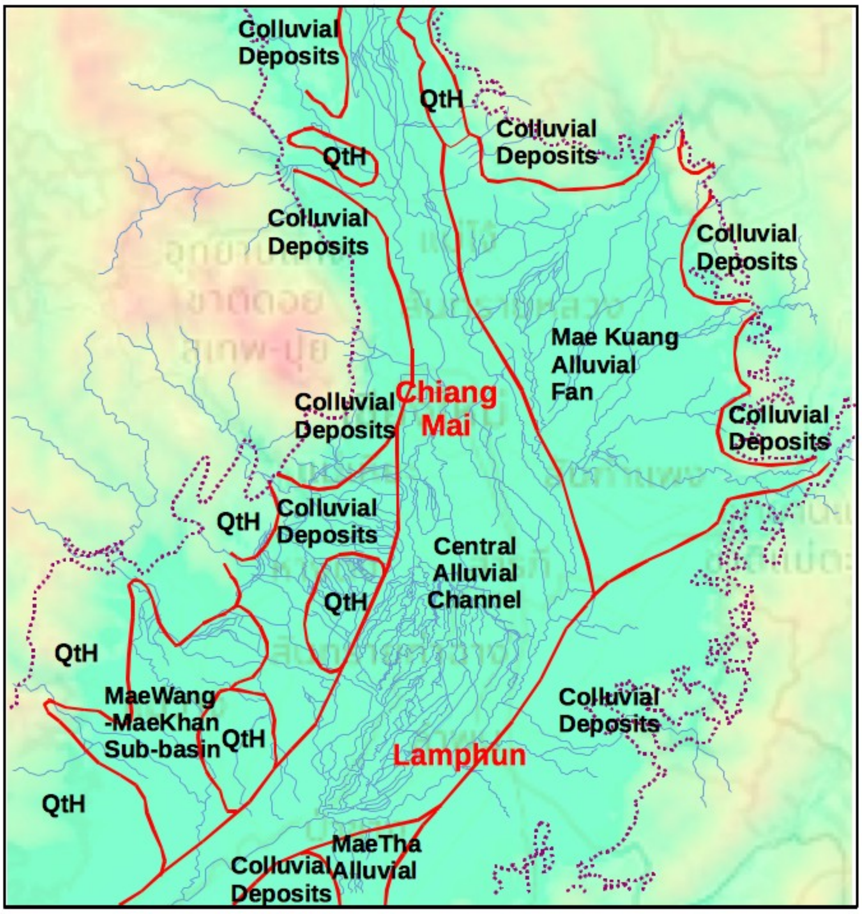


Figure 9. Subdivisions of the Chiang Mai – Lamphun Basin aquifers overlaid on a topographic map. Blue is surface water and dotted purple line is the limit of the basin aquifer (modified from Margane & Tatong, 1999a)

The overall situation in the basin is that aquifer recharge occurs mainly in terrace deposits during July to October and flow towards the central part of the basin and eventually discharge into rivers through floodplain deposits (Margane & Tatong, 1999; Taweelarp *et al.*, 2021). Based on isotopic studies, shallow unconsolidated aquifers are young (5 to 40 years) with younger ages in the northern part of the basin and particularly for the top 40 m of the water table based on ^{14}C and ^{3}H-^{3}He dating (Kamdee *et al.*, 2020) (Fig. 10).

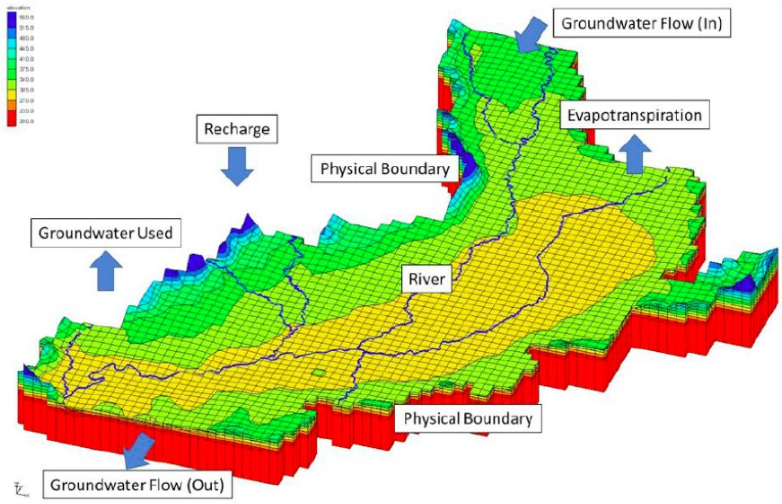


Figure 10. 3D model of the CML Basin aquifer with recharge zone on the edge of the basin and flowing towards the light green and yellow zones (Taweelarp *et al.*, 2021).

3.1.1. Floodplain aquifer

The central fluvial channel is made of Quaternary alluvium sediments of unconsolidated sand and gravels deposited under the high energy conditions produced by the Ping river with silty strata only a minor component. There is no significant lateral extension of various units and correlation between nearby boreholes and wells is not really possible. The floodplain aquifer is 0 to 50 m deep on average and is unconfined for the first 30 m, then eventually semi-confined for the lower part. Wells in this area are shallow with an average of 50 m depth, ranging from 20 to 70 m and have significant hydraulic conductivities of 10 to 100 m/d for standard wells (Lerdthusnee *et al.*, 1981; Margane & Tatong,1999; Pholkern *et al.*, 2015; Taweelarp *et al.*, 2021).

Minor variations occur outside Chiang Mai district. In Mae Rim, the aquifer is mostly at 20 to 40 m deep with 1 to 2 m of clay on top and a hydraulic conductivity of 20 to 200 m/d while in San Pa Tong, the aquifer is also 20 m deep but overlaid by 8 m of clay making it partially confined. A deeper aquifer is also present but has a considerably lower piezometric head than the water table of the shallow aquifer by 15 m (San Kamphaeng) to 35 m (San Pa Tong) (Margane & Tatong, 1999; Pholkern *et al.*, 2015) (Fig. 11).

Due to the unconfined nature of most of the main alluvial aquifer, the water table is relatively vulnerable to surface contamination which is a potential issue considering the urban and industrial growth in the area and the lack of enforcement in ground & water pollution policies (Fig. 16).

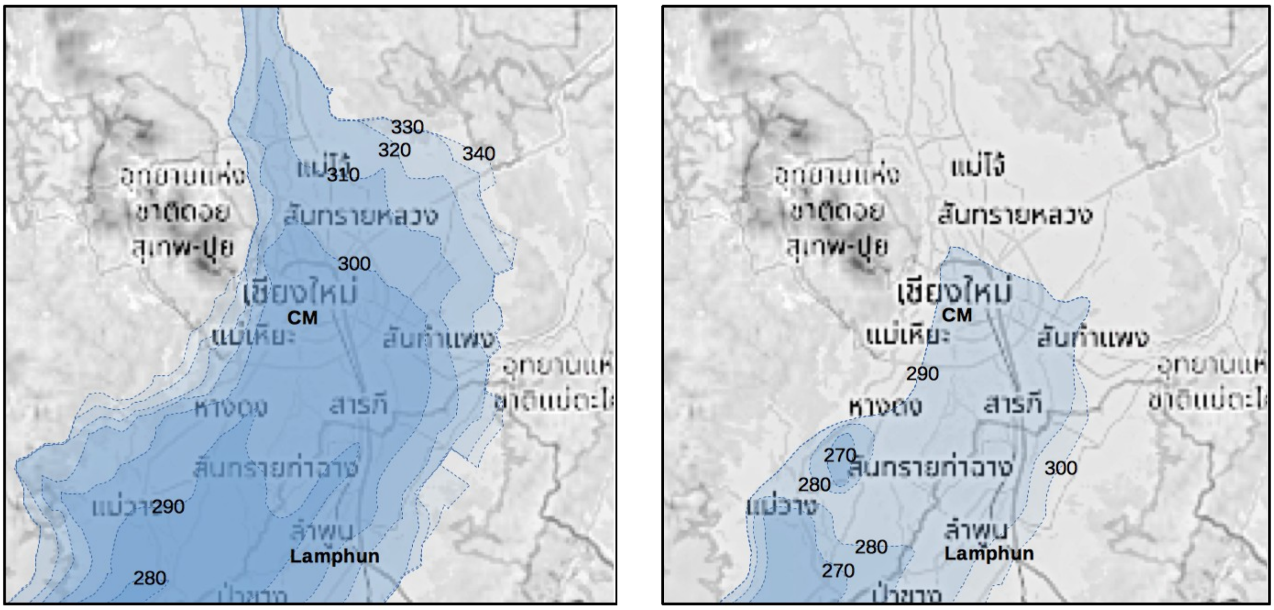


Figure 11. Isopiestic maps of the shallow aquifer (left) at <50 m and deep aquifer (right) at depth below ground above 50 m in 1985 (modified from Margane & Tatong, 1999).

3.1.2. Alluvial fans aquifers & sub-basins

The Mae Kuang alluvial fan is a large hydrogeological domain under San Sai, Doi Saket and San Kamphaeng made of interfingered coarse and fine sediment with coarser granulometry in the northern part. It is the result of alluvial sediments deposited by the Mae Kuang and Huay Bon rivers. The average depth well in this aquifer is 50 m with well capacities of 1 to 20 m/d (?) and measured hydraulic conductivities varying from 5 to 100 m/d (Margane & Tatong, 1999)

Overall, the Mae Kuang alluvial aquifer produces a water of good quality but the southern part has higher TDS levels. Vulnerability to pollution is variable as the aquifer is protected in some places such as the San Kamphaeng-San Sai area by thick layers of silty clay (Margane & Tatong, 1999) (Fig. 12, 16).

The Mae Wang – Mae Khan sub-basin is another alluvial deposit formed by the continuous subsidence in the area, leading to a sand & gravel aquifer with capacities of 50 m/d (?) but with high variability (Margane & Tatong, 1999).

3.1.3. Colluvial aquifers

Colluvial aquifers are present east of Mae Kuang and the southern margin, Huay Bon in the North and the North-West of Chiang Mai as sand & gravel beds but present as channel deposits, producing small catchment areas. The colluvial basins are known as shallow since a few undated wells reach consolidated limestone and shale from the basement. Well capacities are 0.1 to 3 m/d (?) with high volume locally and a hydraulic conductivity below 1 m/d. It is not uncommon to have deep wells of 200 m with several screening level in the area.

The colluvial water table lowers by 1 m per year two decades ago, indicating an already overexploited aquifer in the deeper part. It also present high fluoride concentrations (16.5 mg/l) indicating low flow velocities. For these reasons and the low capacity and conductivity of the aquifer, the colluvial area is rarely drilled on the foothills (Margane & Tatong, 1999) (Fig. 12, 15)

3.1.4. Low Terrace aquifer

Low terrace deposit aquifers are 0 to 150 m thick with an unconfined aquifer of around 30 m on both side of the floodplain and deeper confined aquifers under the floodplain (Taweelarp *et al.*, 2021). The low terrace aquifer is a 900 m thick deposit made mostly of clay with some sand and gravels, providing moderate to high yield of water of good quality (Lerdthusnee *et al.*, 1981).

3.1.5. High terrace aquifer

High terrace aquifer is present on the western margin and a small area of the eastern margin of the basin with 120 to 300 m of poorly sorted sand and gravel beds alternating with silt and clay of late Pliocene and early Pleistocene. The aquifer is unconfined for 30 m either when the high terrace is exposed and when the aquifer below the low terrace is unconfined as well (Taweelarp *et al.*, 2021). These high terrace deposits have high kaolinite content and significant induration leading to low well capacities (<1 m/d) with a piezometric head between shallow and deep part of the aquifer varying by up to 35 m indicating very low recharging rate and rapid lowering of water levels during extraction of a fair to good quality water (Lerdthusnee *et al.*, 1981; Margane & Tatong, 1999).

3.2. Groundwater composition

The water in the CML basin has a low salinity and is relatively hard with variable Ca-HCO_3 balance due to abundant limestone in the upper basin. This equilibrium eventually shift to Na-HCO_3 in the eastern and northeastern part of Lamphun due to cation exchange with clays. This interaction with clays could also be the reason for relatively high fluoride concentration in a large number of samples where it exceeds the recommended WHO limit of 1.5 mg/l of F and tend to increase with deeper aquifers (Fig. 12).

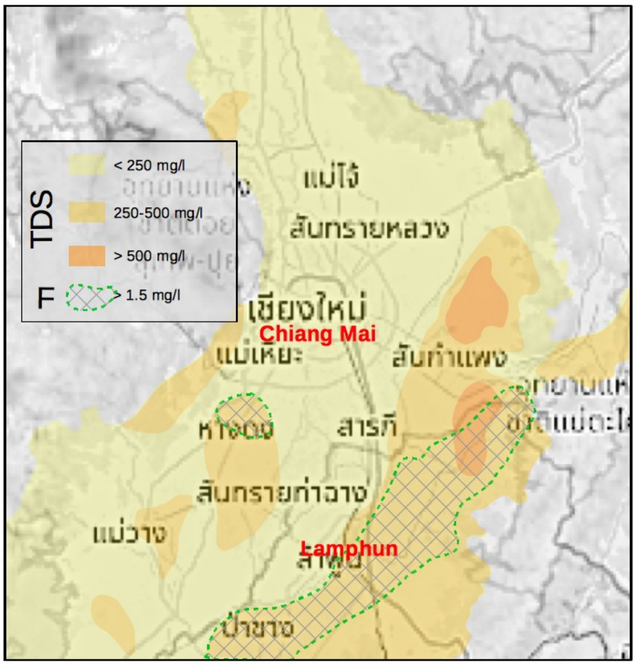


Figure 12. Groundwater quality map for total dissolved solids and fluorine for water pumped between 10 and 80 m below ground (modified from Margane & Tatong, 1999).

Iron levels are above 1 mg/l in 2/3 of the wells and although it is not a health issue, it can be a technical problem as oxhydroxides precipitate and can clog pipes and filters. Iron tend to decrease with deeper wells. Manganese exceeds 0.5 mg/l in half of the wells (Margane & Tatong, 1999).

In the central alluvial channel, which sees the highest groundwater exploitation and high hydraulic conductivities, Fluorides and iron are in relatively low concentrations due to the oxygenated nature of the aquifer and high flow velocities. TDS in this aquifer is mostly acceptable and below 250 mg/l (Taweelarp *et al.*, 2021) but increase towards the eastern edge. (Fig. 12)

3.3. Exploitation

Most wells in the CML basin pump water between 10 and 80 m deep with the highest exploitation potential in the central alluvial channel although the Mae Kuang alluvial and Mae Wang-Mae Khan sub-basin also have high productivity zones despite having a large number (75%) of low (<20 m^3/h) yields wells (Margane & Tatong, 1999). This exploitation can lead to a lowering of the water table up to 1 m/yr in areas of low permeability (i.e. colluvial and high terrace aquifers) as well as overexploited aquifers (Margane & Tatong, 1999) (Fig. 13).

The groundwater recharge rate is estimated between 126 and 143 mm/y for the whole basin (Uppasit, 2004; Taweelarp *et al.*, 2021) with variations as low as 17 to 25 mm/yr in colluvial areas (Intasutra, 1983, Tatong *et al.*, 1997) to 273.2 (Suvagondha, 1979) and 293 mm/yr in the central alluvial aquifer (Tatong *et al.*, 1997) and would represent 11% of precipitation stored in water tables. These estimations are supported by isotopic studies and ^{14}C independently suggests a recharge rate of 25 to 210 mm/yr (Kamdee *et al.*, 2020). Models for exploitation show that the annual groundwater budget in the CML basin is 255 Mm^3/yr with a safe yield of 125 Mm^3/yr (Tatong *et al.*, 1997; Saenton, 2010).

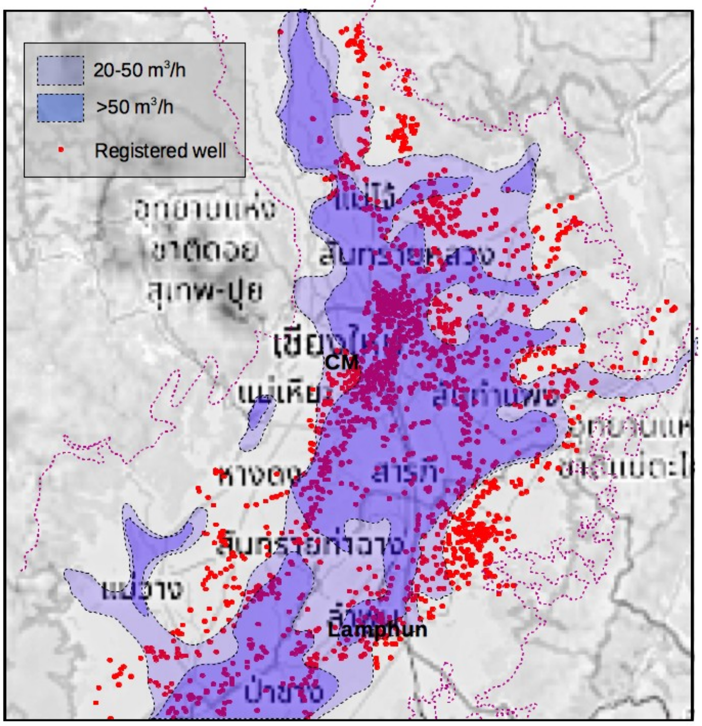


Figure 13. Groundwater extraction potential in the late 90s with a distribution of over 2500 registered wells (as of 2019) (modified from Margane & Tatong, 1999; Taweelarp *et al.*, 2021)

Following the droughts in the 80s and for sanitary reasons, there has been a rising demand in water in the past 4 decades. In the early 80s, it was already mentioned that many houses built outside the municipal area had ground wells for which no record of data exist (Lerthusmee *et al.* (1981)). By the late 90s, there were 21800 drilled wells reports in the CML basin and 20500 of them were private and/or for agricultural purposes with little to no data available except for the 1117 government wells that were used for modeling (Tatong *et al.*, 1997; Margane & Tatong, 1999).

In 2019, 2568 wells had available data, extracting 29.7 Mm^3/yr (Taweelarp *et al.*, 2021). Part of the issue regarding groundwater reserves and management is the inability for the Royal Irrigation Department (RID) to control the drilling and production of wells (Lebel *et al.*, 2009) since most are not metered and only a broad estimation of water withdrawal can be obtained. Based on well use, distribution and type, it is estimated that 40 Mm^3/yr are for domestic use and 200 Mm^3/yr for agricultural use in the late 90s with an estimated recharge between 220 and 250 Mm^3/yr since the shallow part of the aquifer generally does not show visible lowering and is probably balanced (Margane & Tatong, 1999). According to the more recent exploitation model of Taweelarp *et al.* (2021), the current extraction of unconsolidated aquifers at 22 Mm^3/yr could be pushed to a safe yield of 51.2 Mm^3/yr (214%) when imposing a threshold of 2 meters of drawdown. Such yield is however not applicable everywhere since Hang Dong, San Pa Tong, San Kamphaeng and Mae Rim area, following significant agricultural and urban growth and government mitigation of droughts, have shown significant level drops (Taweelarp *et al.*, 2021) (Fig. 14).

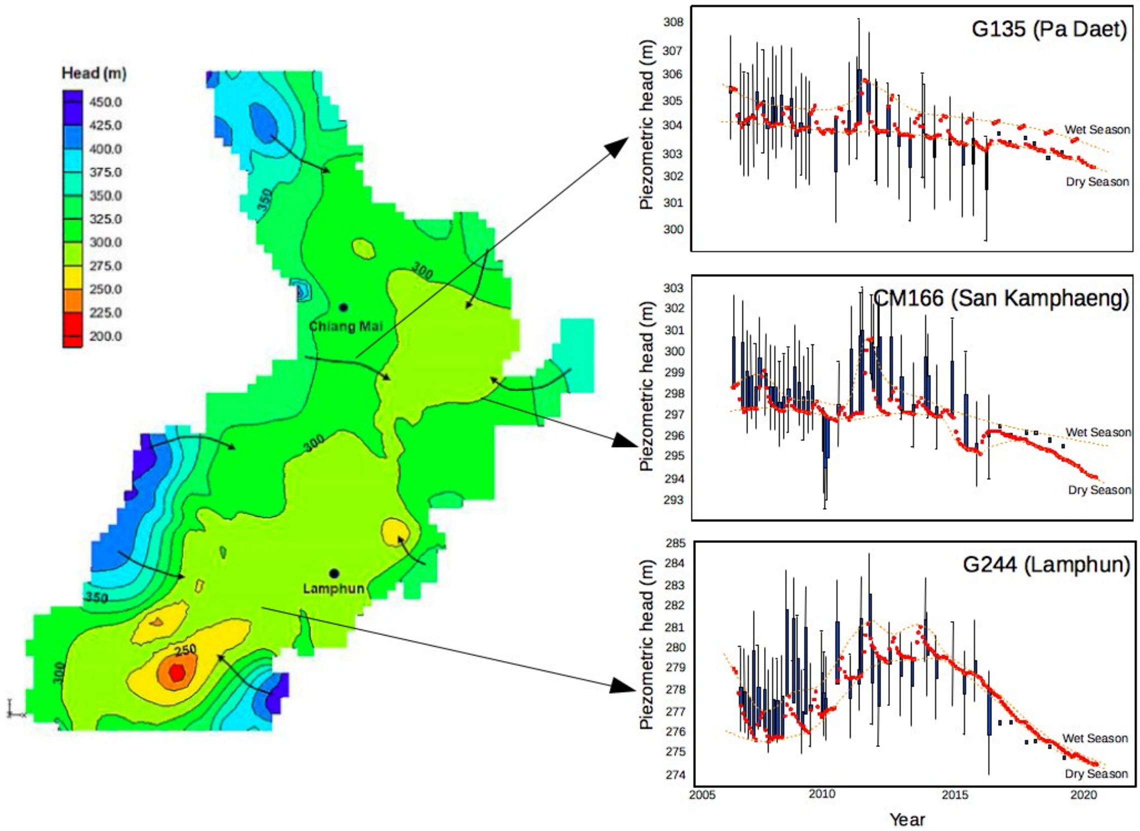


Figure 14. Isopiestic map of the CML basin and piezometric head records in 3 different locations between 2007 and 2020 showing an apparent steady lowering of the water level (modified from Taweelarp *et al.*, 2021).

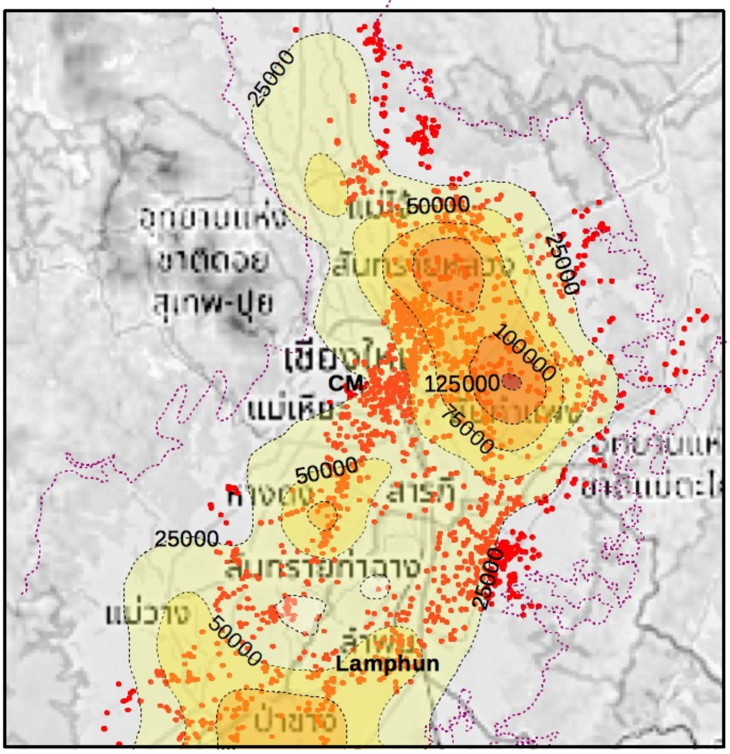


Figure 15. Map of groundwater abstraction from exploitation in m/y.km in the late 90s and the distribution (red dots) of around 2500 registered wells in 2019 (modified from Margane & Tatong, 1999; Taweelarp *et al.*, 2021).

3.4. Risk

The rapid urbanization and industrialization of the CML basin has considerably increased the risk of overexploitation and contamination. In the late 90s, the future development potential of the central alluvial aquifer was considered as good (Margane & Tatong, 1999)(Fig. 15). However, recently, modeling of the storage coefficient (and therefore the yield) of unconsolidated aquifers is below normal and could indicate that the future potential for groundwater is less than ideal especially in the last decade that has seen a significant drop in groundwater recharge (Taweelarp *et al.*, 2021)(Fig. 14).

The issue of contamination is minimised for aquifers protected by low permeability soils or rock cover of significant thickness and perched aquifers and artesian water tables. Such natural protection is found in the NW & NNE of Chiang Mai, West of Lamphun, East & North of San Pa Tong and around Mae Wang (Margane & Tatong, 1999). In many places, and particularly within the central alluvial channel, aquifers are unconfined and the risk of surface pollution is high as it lacks protection from a thick and continuous clayey or silty layer. Ideally, industrial plants and landfills with hazardous management should be banned from these areas (Margane & Tatong, 1999; Hui Yian Lee *et al.*, 2024) (Fig. 16). Deep & artesian wells and even some surface ponds and reservoirs in rural and remote areas are significantly less polluted with a low risk due to limited pathways for contamination (Hui Yuan Lee *et al.*, 2024).

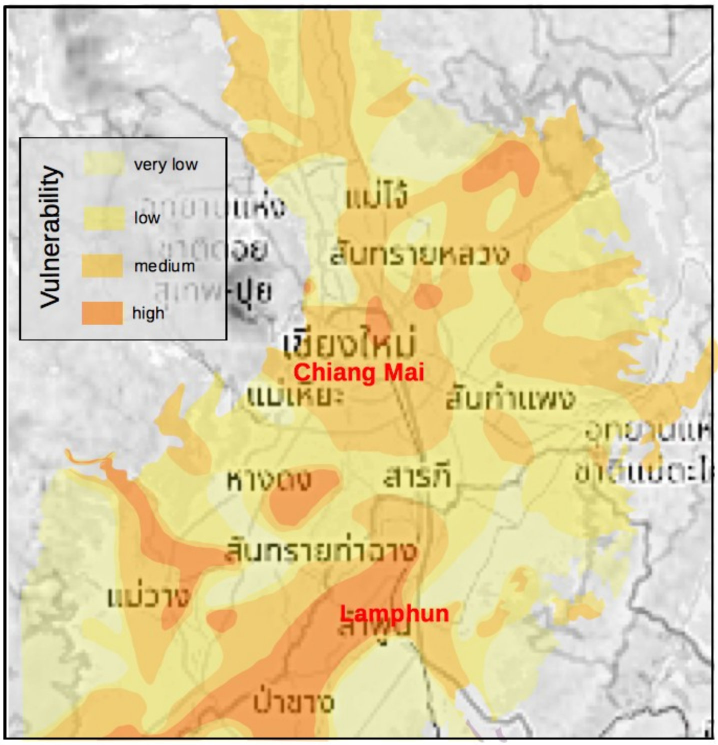


Figure 16. Relative vulnerability of the CML basin aquifer based on the characteristics of the unsaturated zone (modified form Margane & Tatong, 1999)

4. Flooding characteristics in the Upper Ping catchment

A few categories of floods are generally acknowledged in the literature with three of them present in Chiang Mai. Pluvial floods appear during heavy rainfall through rain accumulation and insufficient drainage leading to local rise and sometimes prolonged high rainwater levels. Flash floods are caused by heavy rainfall on a topographic high and extreme accumulation of runoff drainage in a localised area for a relatively short time. River floods are caused by a rise in river or canal water level causing extensive and prolonged flooding. Other categories such as coastal floods and storm surge and groundwater floodings are not types of event seen in the inland region of Chiang Mai and the upper Ping (Tachaudomdach *et al.*, 2021).

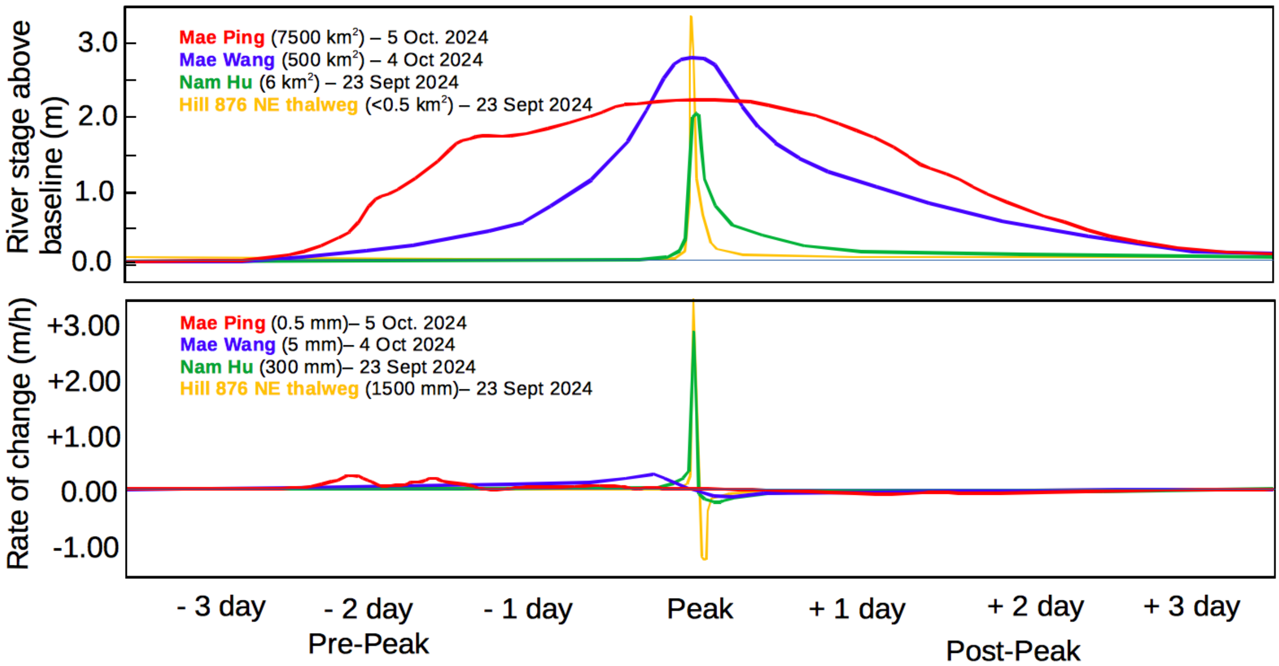


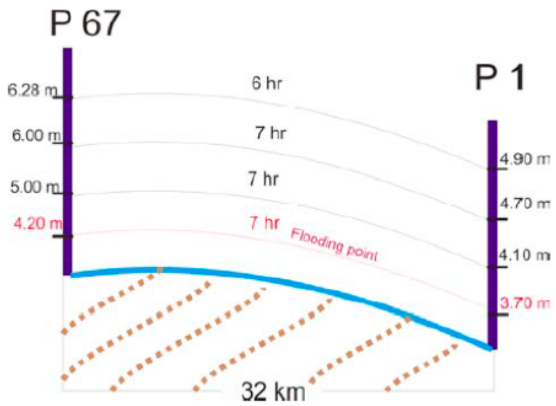
Figure 17. Effect of catchment size on the characteristics of floods. Top: Water level variations for different catchment size. Red and Blue are large and medium catchment areas producing river floods while green is a small catchment producing a flash flood. Yellow is a very small catchment affected by a debris flow. Bottom: Rate of increase and decrease in flood waters ranging from a maximum of 10-20 cm/h for river floods, up to 1 or 2 m/h in flash floods and sudden for debris flow. Dimension values are the maximum grain size transported by the event at peak flow.

Pluvial floods occurs in topographical lows where drainage is insufficient. They often occur in farmland but are mostly noticeable in poor suburbs of Chiang Mai where infrastructure is inadequate, with rainwater accumulating in a cuvette. Some of these areas in the city experience such floods 2 to 4 times per year with water rising as high as 1.5 m and barely flowing towards the nearest significant drainage. Compared to similar floods in other Thai cities, pluvial floods in Chiang Mai are fortunately rarely associated with sewage floods. Local floods are rarely reported as they are quite common, often of low intensity and in socially disadvantaged areas of Chiang Mai that does not attract a particular attention from the media.

Flash flooding occurs along the foothills of mountain ranges around the CML basin and subordinate creeks from tributaries. Intense rain events can happen up to 10 or 15 times per year, causing water levels occasionally well above 1 meters and with a high velocity flow sometimes above 5 m/s. These floods are short lived, from a few hours to a day but can be quite severe and destructive. Flash flooding are very common but get only reported when the damage is extensive or it affect an economically important area (Fig. 17).

River & canal flooding occurs in the direct vicinity of these waterways and excludes overflowing canals designed as stormwater channels which have more flash flooding characteristics. This type of flooding occurs in many poor low-lying or rural areas and it is not uncommon to have floods 2 to 5 times per year with water height less than 1 meter lasting for 3 to 4 days. In such flooding, the water is running at up to 2 m/s. River flooding is a common phenomenon in rural areas of fluvial basins of South East Asia and part of the traditional way of life. However, for flooding with a high river stage, it affects larger areas and potentially overwhelm protected section of the river, leading to flooding of economical areas and cutting major roads. Such events happen every few years and receive important media coverage.

While pluvial floods have no warning other than weather forecasts and direct evidence of heavy rainfall, flash floods typically have a few tens of minutes of possible warning following the beginning of a rainstorm. Due to the nature of catchments producing flash floods, the distance between precipitation and flooding area is generally not that far and the rainfall causing the event can be directly experienced or seen in the distance. River floods can occur a few hours to several days after an intense rainfall depending on the location. In Chiang Mai, the typical forecast for flooding is around 48 hours for flooded headwaters to reach the city (Lim & Boochabun, 2012). However, peak flow and its intensity is estimated at a shorter time scale of 6-7 hours, which is the time it takes for water in station P.67 to reach P.1. (HWMC, 2007, 2012). The positioning of P.67 was established from experience from previous floods with a relatively well established relationship that +4.7 m on P.67 will equal +3.7 m (current flood level in Chiang Mai city) at P.1 within 7 hours and is reduced to 6 hours for predicted P.1 levels above +4.8m (Fig. 5, 18). Past values of 8 hours in the 1998-2001 period are possibly due to different channel conditions and specific rain patterns (Patsinhasanee, 2004; Chatchawan, 2005). In terms of accuracy in forecasting the intensity of a peak flow during a flood, error at +6 hours is now generally inferior to ±0.1 m (Chaipimonplin, 2010).



Arrival time in high flow velocity conditions to P.1 river stage station

Station	Location	Downhill flow time (h) 1998-2001	2005	Distance
P.20	Uppermost Ping [Chiang Dao]	25 h	33 h	103 km
P.4A	Mae Taeng (Mae Taeng]	24 h	20 h	52 km
P.21	Mae Rim [Mae Sa]	14 h	19 h	23 km
P.75	Upper Ping [Mae Ho Phra]	-	16 h	50 km
P.67	Upper Ping [Mae Faek Mai]]	-	6 h	34 km
P.1	Nawarat Bridge [CM]	-	-	0 km

Figure 18. RID diagram of river stage correlation between stations P.67 and P.1 and arrival time and various high flood flow time for different stations upstream from P.1 (modified from Chaipimonplin, 2010; RID Database).

4.1. Description of Ping river flooding

For flooding to occur in the inner city (at P.1 gauging station, near Nawarat Bridge), the current water level has to reach +3.7 m above the river bed (304.2 msl) which is ideally equivalent to >460 m^3/s but varies depending on the state of the river channel and some dynamic effects so that in 2024, it was closer to 400 m^3/s (Fig. 19). The conveyance capacity of the main channel shows that 460 m^3/s caused flooding in 1972, 2004 and 2005 but not in 2002 or 2006 (Chaipimonplin *et al.*, 2011). The relationship between flood volume and river stage is updated annually by the RID and with the exception of major floods decades ago, in significantly different situations, the relationship is quite accurate (Vongtanaboon *et al.*, 2008).

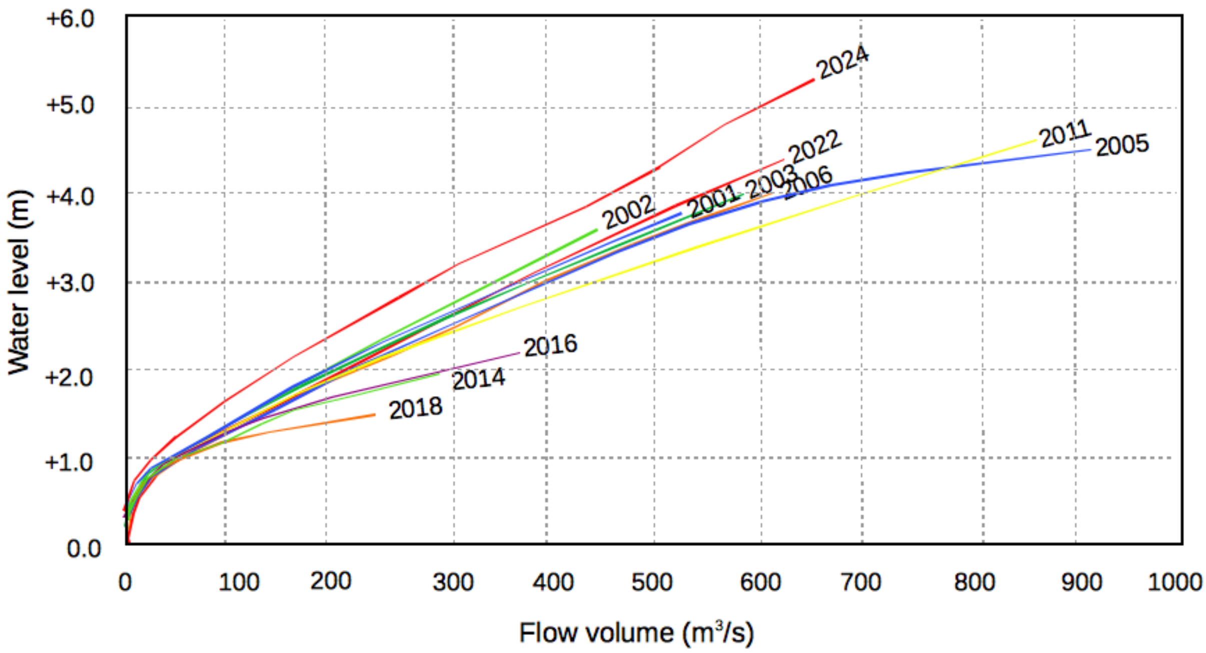


Figure 19. Relationship between river stage (in meters above the P.1 reference level) and the river volume flow. While most floods follow the same curve, the flood of 2024 is clearly an outlier where the conveyance capacity of the Ping river was significantly lower (data from RID)

Before 2004, the flooding level in P.1. was +3.4 m so that all flood occurrences are not always equivalent when comparing historical events and hydrological comparison have to be made on water stage and volume flow to accurately compare past floods as hydrological events. Starting in 2004, the Ping river expansion project was initiated, raising flood protection to +3.7 m in Chiang Mai city (Chaipimonplin *et al.*, 2011; Tansar *et al.*, 2021) (Fig. 20, 27).

In 1991, a first flood map was produced by the Hydrology and Water Management Centre (HWMC) to anticipate risk in impacted areas (Jarungrattanapong & Manasboonphempool, 2011). The map was updated several times as more data become available and the river system and management changed through time. In 2005, the Civil Engineering Natural Disaster Research Unit (CENDRU) produced a map of flood risk for Chiang Mai city with seven zones downstream of P.1. based on flooding in 1994, 1995 and 2005 and the map has been mostly unmodified since and widely share in media outlets (Chatchawan, 2005; Chaipimonplin, 2010; CENDRU, 2013) (Fig. 21).

Chiang Mai has a relatively long river gauging record for South East Asia, with almost continuous data from 1921 to the present time (Lim & Boochabun, 2012) as well as a number of rain gauge in the Upper Ping basin that are almost continuously operating for the past century (Lim *et al.*, 2012). Values of a river stage as high as +3.7 m in P.1 show that such heights are reached in 51.6% of all rainy seasons of the past century (Lim & Boochabun, 2012) making it a biennial event (Fig. 27).

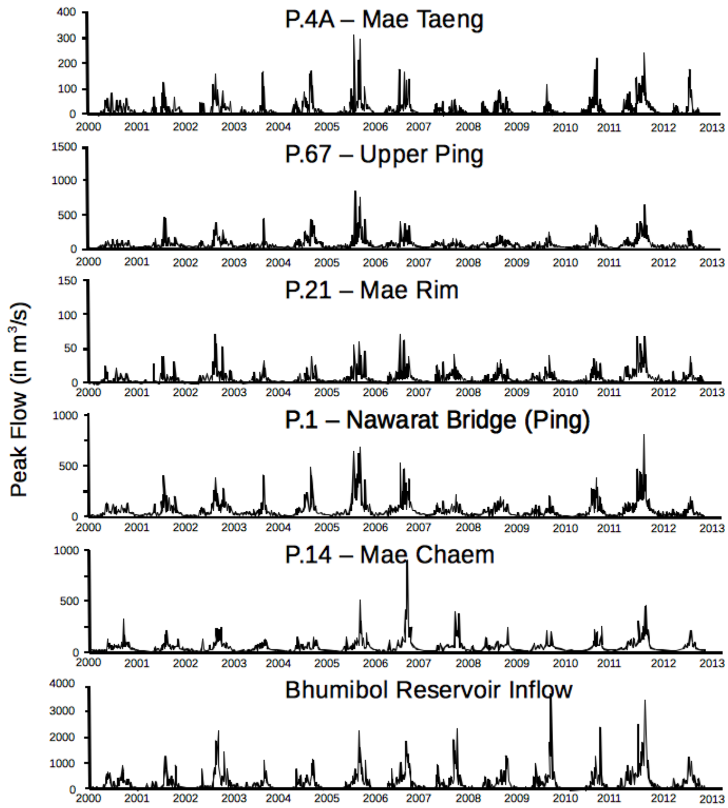


Figure 20. Records of floods between 2000 and 2013 in various measuring stations of the Upper Ping and Bhumibol Reservoir (modified from Wuthiwongyothin *et al.*, 2017)

The rainy season is dominated by storms of moist air moving NE from the Indian Ocean, creating conditions over Northern Thailand typically associated with the wet season such as cloudy skies and frequent rainfalls, leading to this low intensity flooding around +3.7 m in P.1. if no water management was in place. However, large floods at +4.0 m are preferentially associated with tropical depressions (cyclones, storms) moving westward from the South China Sea (Wood & Ziegler, 2008). Such meteorological events bring intense rainfall in the upper catchment of the Ping river (Garden, 2007) and typically occur in August-September, when the ITCZ is over Northern Thailand and the base flow of the river is the highest due to rainfall over the previous months (Lim & Boochabun, 2012). With no available water storage in the catchment and high soil moisture levels, important rainfall are directly associated with important runoff (Chaipimonplin, 2010) (Fig. 6).

4.1.1. Pre-1950s

In 1933, 1937, 1942 and 1945, significant flooding is recorded in Chiang Mai but are not particularly described. However, indirect effects can be guessed from downstream locations, such as the 1942 Bangkok floods that lasted for three months (Proverbs *et al.*, 2012).

4.1.2. 1952 Flood

The flood of 1952 is classically considered as the largest flood of the past century. The flood was caused by high monsoonal rainfall in September where typhoons Louise and Nona have only played a role in saturating the catchment soils in the weeks before (Lim & Boochabun, 2012). The peak of the flood is estimated to be above 830 m^3/s (Wood & Ziegler, 2007) but lower, possibly more realistic, values are also published such as 490 m^3/s (Lim & Boochabun, 2012; RID database). Accounts of the flood describe large parts of Chiang Mai as inundated, which, considering the size of the city at the time, would include most lands between the walled city and the river (Fig. 22).

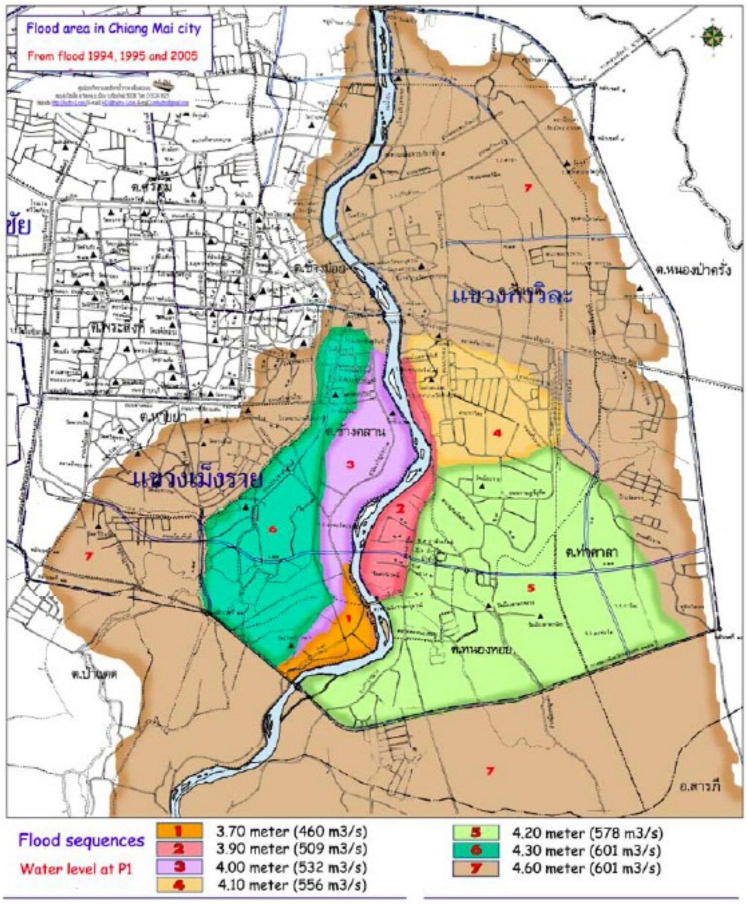


Figure 21. Flooding risk for various water levels of the Ping river at P.1. (CENDRU, 2013)

4.1.3. 1973 Flood

In 1973, an important flood occurred, in conditions of a saturated catchment caused by cyclone Anita in mid-July, which didn't produce any flooding. The following tropical depression, cyclone Jones at the end of August, caused the peak flow of the 1973 flood at 720 m^3/s (Lim & Boochabun, 2012) (Fig. 22).

4.1.4. 1980s flood

In 1987, a major flood reached +4.53 m in Chiang Mai (Chaipimonplin, 2010) and in early October 1989, an intermediate flood reached +3.82 m.

4.1.5. 1994 flood

In 1994, a first flood occurred on the 19th of August due to heavy rainfall and reached +4.12 m. A month later, on the 14th of September, the crossing of typhoon Harry over Northern Thailand produced another flood at +4.43 m. In the following couple of years, the city centre of Chiang Mai has been flooded 5 times, notably the +4.27 m flood in 1995 (ONEP, 2006; Wood & Ziegler, 2007, 2008; Chaipimonplin, 2010; Gale & Saunders, 2013).

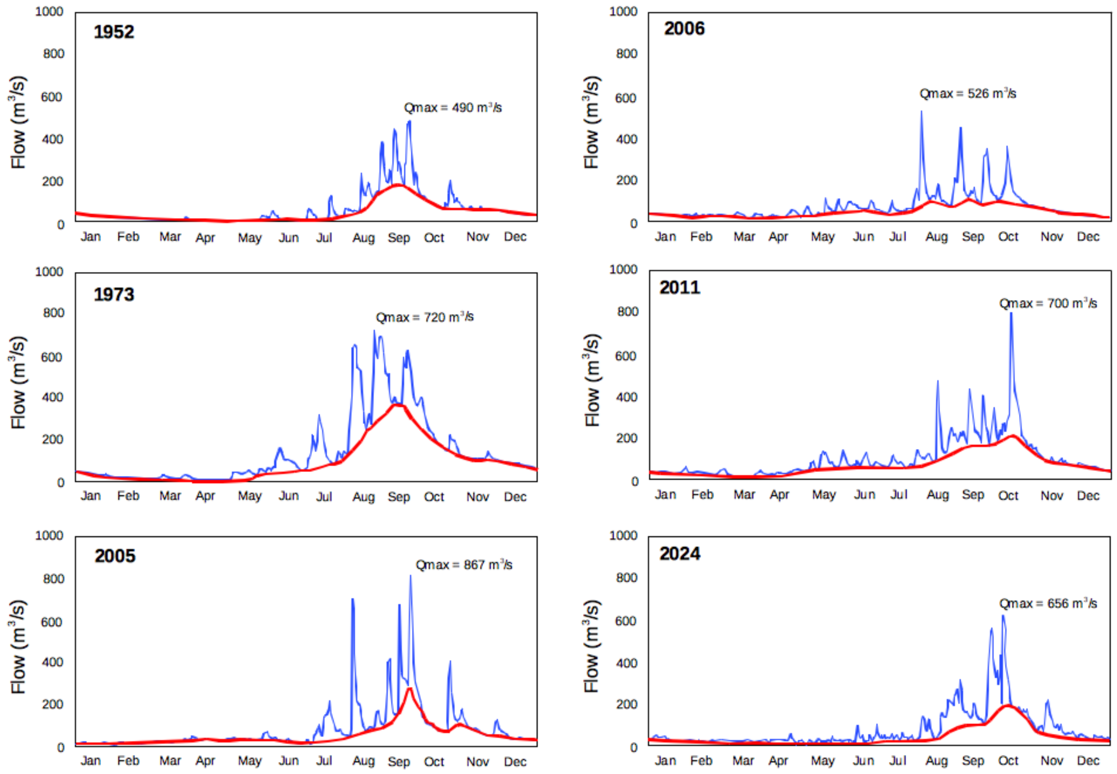


Figure 22. Flood profiles of several years with major floods. The blue line is the hourly measurement of river stage translated into volume flow while the red line represents the base flow of the river at the time of the flood (modified from Lim & Boochabun, 2012 and RID data).

4.1.6. 2001 floodings

In 2001, Typhoon Usagi has caused flooding in the Mae Chaem river and numerous flash floods in the Northern region causing significant local damage (Wood & Ziegler, 2007; Lim & Boochabun, 2012) but no flooding in Chiang Mai City.

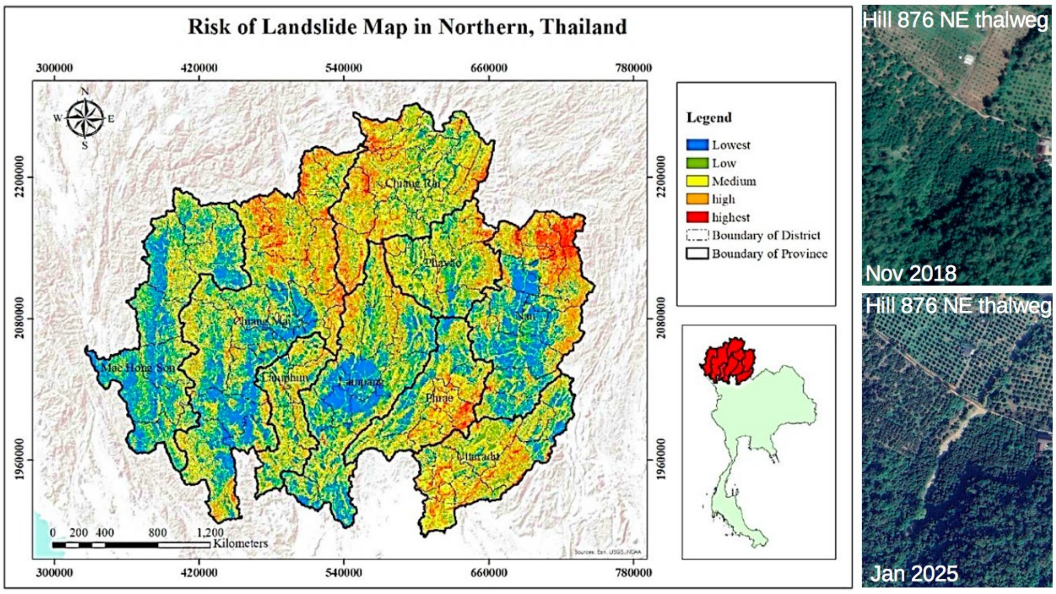


Figure 23. Map of estimated landslide risk in Northern Thailand (Yongsiri *et al.*, 2023). Right: Comparative satellite pictures of a small debris flow in 2024 in Mae Wang (see Fig. 30d).

4.1.7. 2005 Floods

2005 is possibly the largest flood of the past 100 years and was a series of five floods from mid-August to October, with two of them being exceptionally large (Fig. 22). At the end of the second week of August, a low pressure through bringing heavy monsoon conditions dropped 100 to 200 mm of precipitations over Northern Thailand, causing numerous local floods, flash floods and mudslides over the region (Fig. 23). The Ping river rose at 12 to 14 cm/hr and reached peak flow in Chiang Mai at 6 pm on the 14th of August with 747 m^3/s, equivalent at the time to +4.90 m in P.1 where it remained for around 8 hours for a total 51 hours of flooding (Chaipimonplin, 2010).

In the following weeks, additional rainstorms over Doi Suthep-Pui produced flash flooding above the drainage capacity, flooding roads and bridges in the western part of the city (Jarungrattanpong & Manasboonphempool, 2011) and a month later, tropical storm Vicente crossed Indochina and created a second major flood in Chiang Mai on the 21st of September with 485 m^3/s of water reaching +3.80 m above the river bed.

A week later, at the end of September, Typhoon Damrey passed over Thailand bringing rain in excess of 300 mm over three days in Chiang Dao (while Chiang Mai only received 15 mm). This upstream rainfall created a flood at 750 m^3/s reaching +4.93 m in Chiang Mai and keeping the area flooded for 82 hours (Chaipimonplin, 2010). The floodplain itself was under around 1.68 m of water (Lim & Boochabun, 2012). Flash flooding, mudslides and slope failures are described along roads as well (Wood & Ziegler, 2008). Values for the peak flow in P.1 vary widely between publications, from 679 m^3/s (Boonrawd & Jothityangkoon, 2015) to 750 m^3/s (Wood & Ziegler, 2007), 754 m^3/s (Chaipimonplin, 2010), 867 m^3/s (Wood & Ziegler, 2008; Lim & Boochabun, 2012), 912 m^3/s according to the RID model and even 1300 m^3/s (Jarungrattanapong & Manasboonphempool, 2011). This last value is doubtful and lacks any reference, calculation or details to support such extreme flood. It is worth noting that while the floods in most areas lasted 3 to 7 days, there are some rural and poor districts that have been flooded for more than a month continuously during those floods (Jarungrattanapong & Manasboonphempool, 2011). The 2005 floods are estimated to have affected 250000 people, 5 deaths and caused around 1 billion baht of damage (Wood & Ziegler, 2007)(Fig. 22, 24).

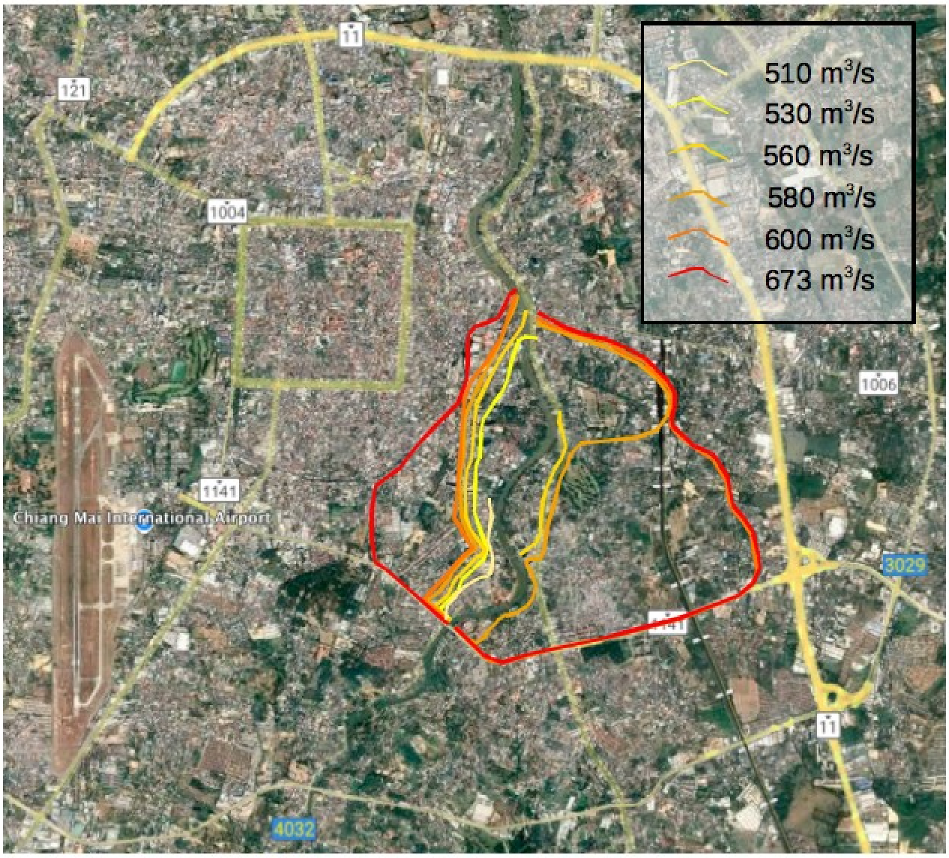


Figure 24. Flood map during the 2005 floods that would eventually be combined into a synthetic document produced by CENDRU in 2013 (see Fig. 20). It is likely that the map is a snapshot of a temporary situation of the flooding front as downstream locations would also have been flooded (modified from Boonrawd & Jothityangkoon, 2014).

4.1.8. 2006 Floods

This year is remarkable for the flooding of Uttaradit and Sukhothai in May as Typhoon Chanchu caused heavy precipitation on the Yom and Nan catchment. Although not the Ping river, it shows that flooding can occur outside the end of the rainy season in some circumstances (Wood & Ziegler, 2007)

Later that year however, a major flood (10 year recurrence) was observed in Chiang Mai with heavy monsoonal rain as the apparent sole cause (Lim & Boochabun, 2012)(Fig. 22).

4.1.9. 2011 Floods

Intense rainfall occurred at the end of July when the tropical depression Nock Ten dropped 100 to 200 mm/day of rain as the largest rainfall event of the year. However, the lack of soil saturation limited the runoff and flow volume at P.1 was 430 m^3/s which was below the flooding threshold in Chiang Mai (Komsai *et al.*, 2016).

By October, Northern Thailand had experienced 5 tropical storms and a heavy monsoon with a rainy season rainfall 20 to 60% above normal (Reda *et al.*, 2012). In early October, the rainfall averaged 50 to 70 mm/day and combined with necessary dam releases, it produced a 700 m^3/s flow in P.1 reaching +4.95 m. The flood covered 335 km^2 of land within Chiang Mai and caused 7 to 8 billion baht of damage that are included in the estimated 45 billion baht damage of the whole 2011 floods in Thailand (Lim *et al.*, 2012; Komsai *et al.*, 2016) when Bhumibol dam reached capacity and eventually let all of the Ping inflow diverted downstream into an unregulated Chao Phraya, flooding the Central Plains and Bangkok (Bidorn *et al.*, 2016)(Fig. 22).

4.1.10. 2022 Floods

In 2022, an important flood occurred on the 5th of October, reaching +4.75 m at P.1. It was related to heavy rain and a necessary release from the Mae Ngat reservoir.

4.1.11. 2024 Floods

The floods of 2024 have not been reviewed in academic papers at the time of writing. However, some observations can be made such as the presence of Typhoon Yagi, 1 out of the 4 ever recorded category 5 cyclone in the South China Sea, that made landfall in North Vietnam and passed over Thailand on the 8th of September, creating marginal floods in the Ping river (Fig. 22).

On the 22nd of September, tropical depression Nº8, also from the South China Sea, passed over Northern Thailand with abundant rainfall for several days, causing various landslides, slope failures and the closure of the Chiang Mai – Lamphun railway for a few days. This raining event caused the first major flood on the 26th of September, stabilizing at +4.45 m in P.1, followed a few hours later by a second runoff bringing the flood to +4.93 m (Fig. 22).

On the 3rd of October, the monsoon through moved and stalled over Northern Thailand bring abundant moisture and extensive rainfall on an already oversaturated catchment. As a very significant proportion of rainfall was brought to the rivers, the Ping river reached its peak flow on the 5th of October at +5.30 m for a flow volume estimated at 656 m^3/s (RID Database). The duration of the flood in Chiang Mai lasted 102 hours but some low farmland downstream of the city were constantly flooded from mid September to the end of October (Fig. 25).
The preliminary estimation of the cost of these floods is around 10 billion baht which represents a couple of percent of Chiang Mai province economical output (Fig. 26).

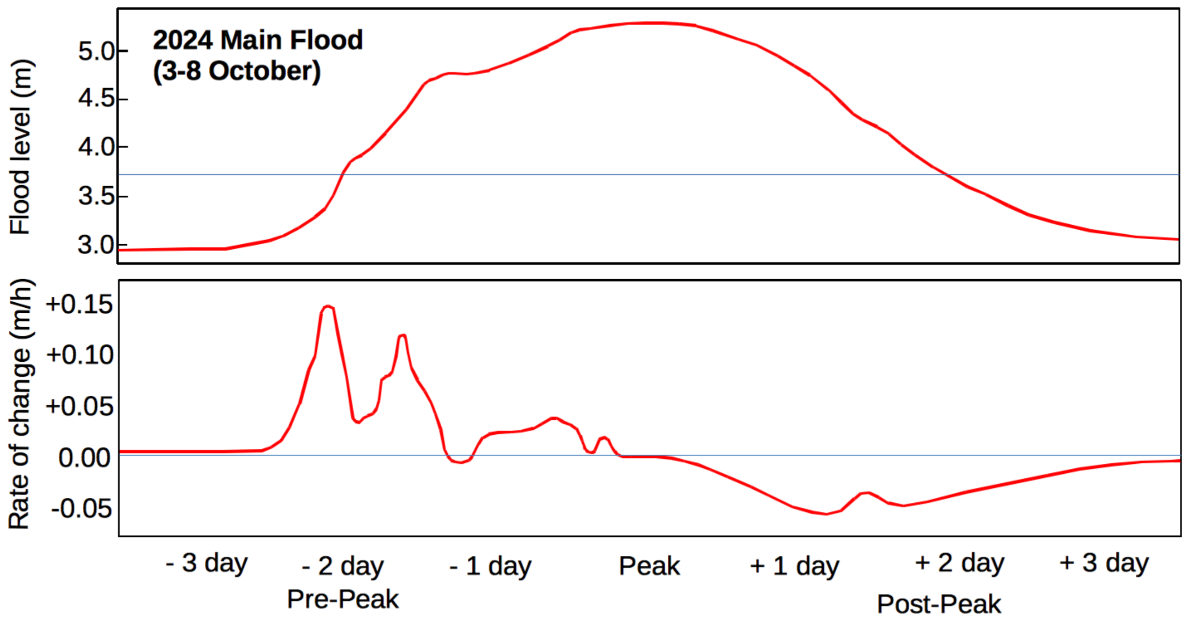


Figure 25. River flow characteristics during the second major flood of 2024. Top: river level at P.1 (the horizontal line represent flooding at +3.7 m). Bottom: Rate of change in meters per hour of the Ping river in P.1. showing 3 pulses leading to the peak flow during the night between 5th and 6th of October (Data from RID).

4.2. Causes of Ping River flooding

Heavy rain is always the primary cause of flooding but several preliminary conditions and rainfall characteristics are required for heavy precipitations to produce a flood. Although river floods are often linked to the downpour from tropical storms and depressions (1973, 1994, 2005, 2024), a heavy monsoon can also lead to a situation where flooding occurs (1952, 1989, 2005, 2011, 2022, 2024) particularly when the soil is saturated beforehand (Lim & Boochabun, 2012). At a seasonal scale, the state of the El Niño Southern Oscillation (ENSO) has an influence but is not a systematic effect. A strong La Niña was recorded in 1973, 2011 and 2022 and associated with major floods. However, La Niña was also strong in 1998-2000 and 2008 without any significant flood. On the other hand, there was major flooding in 1952, 2005 and 2024 while the state of the ENSO identified as neutral. Minor floods and flash floods have an even lower correlation factor with ENSO status. For example, in 2001, a weak El Niño period, tropical cyclone Usagi produced some damage through flash flooding (Lim & Boochabun, 2012) and the overall frequency of flash floods make the correlation with ENSO insignificant.

Before the 1980s and the strong anthropogenic influence on the Ping river catchment, the effect of human presence was minimal and all historical floods have heavy rain as the obvious cause to medium and major floods (Chaipimonplin, 2010). In the past three decades however, the intensity of floods in Chiang Mai city have increased while their occurrence has decreased and several causes can be hypothetically identified to explain such trend (Fig. 27).

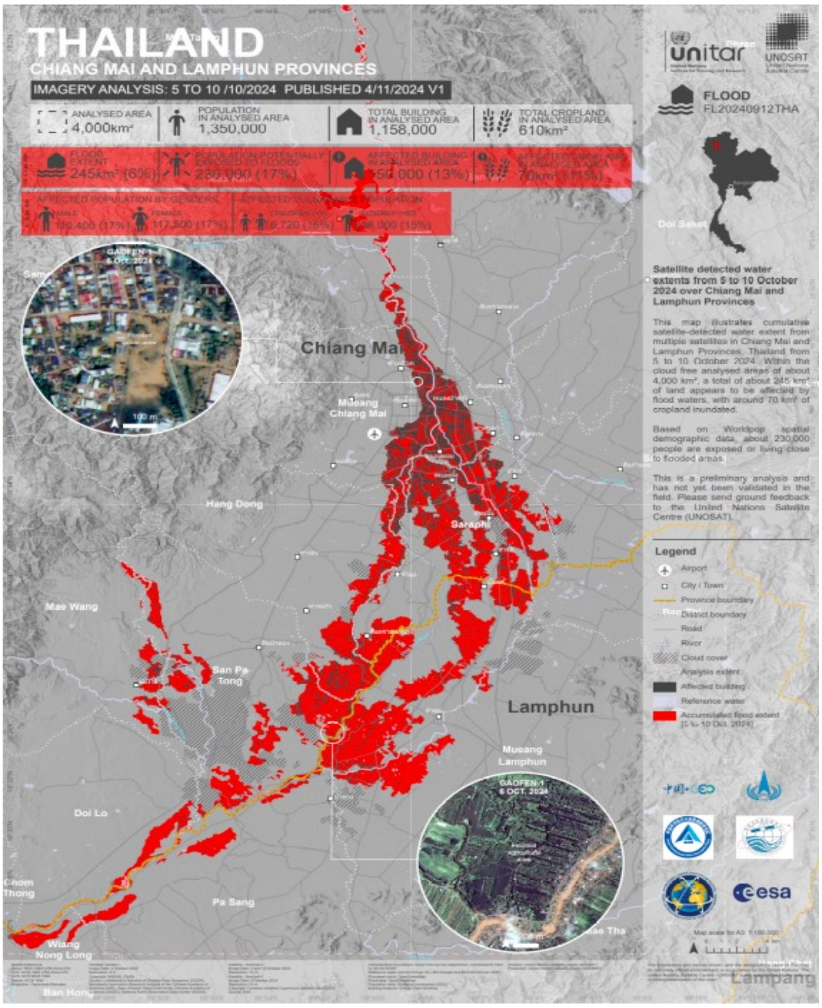


Figure 26. Post-flood satellite imagery analysis of the Chiang Mai-Lamphun basin with flooded zones marked in red (UNOSAT, 2024).

- Deforestation has been suggested as a cause of increased flooding in the last two decades and particularly for the 2005 floods (Chatchawan, 2005; Garden, 2007; Sophhonphattanakul *et al.*, 2009). However, although 2005 and 2011 floods had historically high volume flow, there isn't a trend towards higher average peak flows in terms of volume (Fig. 27). Any effect that deforestation could have is not an isolated factor. Some authors have expressed that the deforestation effect is only minor on the runoff in the Upper Ping river basin (see 6.1.2. and elsewhere).

- River encroachment occurs when land is acquired from river corridors and available water bodies through landfill, rock dumps but also planting aquatic species such as water hyacinth, promoting siltation. The issue was known prior to the big floods that occurred in the last 20 years (2005, 2011, 2024) and has been described as restricting the width of the Ping river as much as 1/5th of its original size (Jompakdee, 2004; Laonamsai *et al.*, 2023). In 2005, encroachment by residents and public agencies on the main channel for housing, restaurants and government offices has been considered as a factor that created a bottleneck effect and higher river stage during flooding within the city (Jarungrattanapong & Manasboonphempool, 2011). There has been some attempt to limit such practices in the years that followed but also an approach of 'what is done is done' leaving significant remaining encroachment.

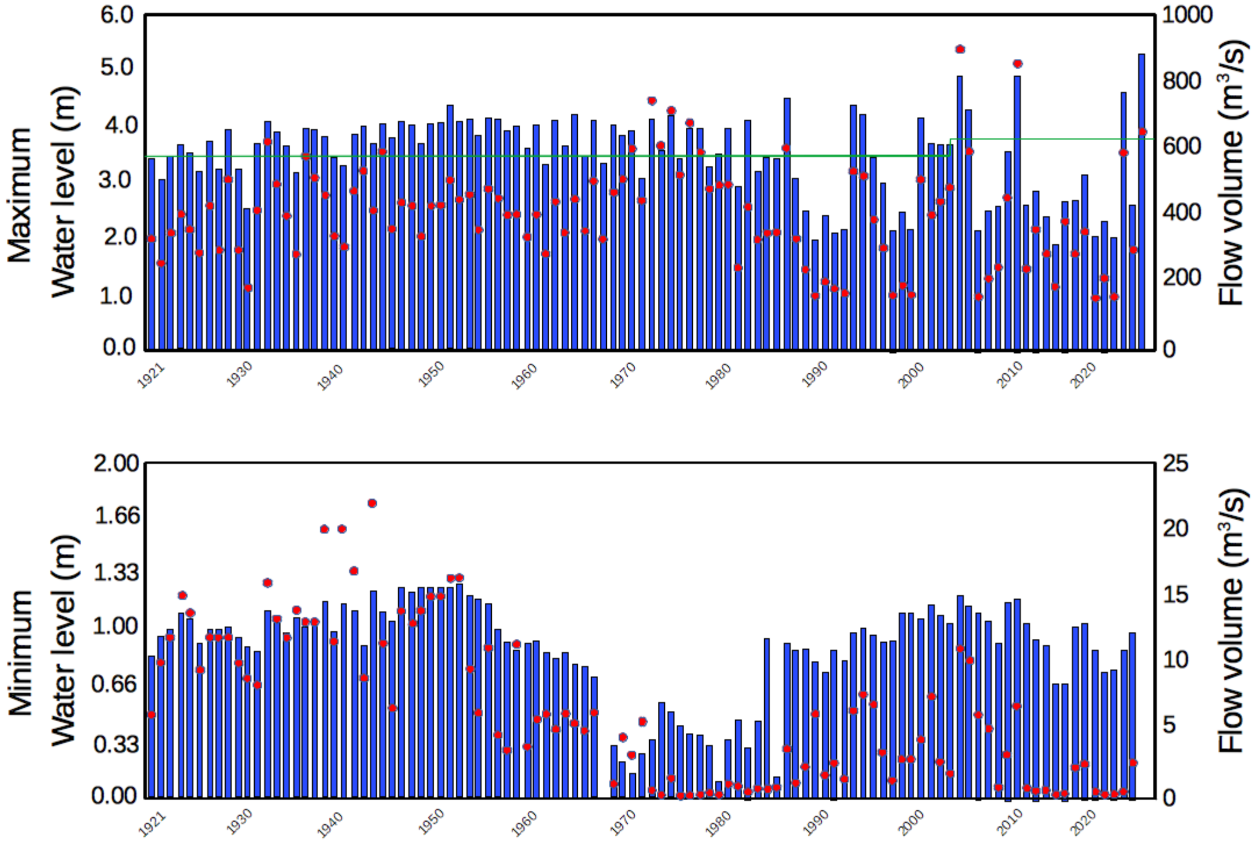


Figure 27. Historical records of water level (blue columns) and associated flow volume for peak flow (red dots) during the rainy season and lowest levels during the dry season (inspired from Lim & Boochabun, 2012).

- Additionally to direct river encroachment, the urbanization and industrialization of the CML basin and the development of Chiang Mai as a primate city in Northern Thailand has produced a lot of infrastructure along the Ping river and in the floodplains (Chatchawan, 2005; Sophhonphattanakul *et al.*, 2009)(Fig. 28). It is not an entirely new phenomenon since several naming of areas of Chiang Mai, even in older part of the city, show that some lands were reclaimed in historical times and toponyms such as หนอง ('nong') in their suffixes (i.e. Nong Hoi, Nong Pratheep, Nong Phueng, Nong Prakang, etc.) are interpreted as 'swamp'. Such areas would have been prone to be flooded by any rise in the base flow of the Ping river in a natural system. In addition to these historically low-lying areas, the last few decades have seen an abundance of new earthworks in the form of elevated roads now crisscrossing the metropolitan areas, modifying the natural drainage of the flood plain (Fig. 28) and extensive landfills for large housing estates that significantly disrupt the flow of floodwaters and reduce the capacity of the floodplain to absorb floods (Manuta *et al.*, 2006).

- Regulated agricultural practices that are now widespread over the basin have a direct effect on water management through irrigation and requirements for water from reservoirs (Manuta *et al.*, 2006). While historical management had a minor impact on the flow of water (see 6.1.1), the construction of larger, deeper weirs and dams, large reservoirs and a large scale management of water resources has profoundly changed the seasonal flow of the Ping river as well as significant droughts and floods.

Finally, some authors also blame climate change for the observed increase in flooding in Chiang Mai (Phongphanich *et al.*, 2014 and numerous non-academic documents). As seen in the appropriate chapter (see 7.2.2), the issue of climate change is a lot more complicated than a simplistic blanket statement that floods are caused by global warming; the absence of trend in peak flow volume is indicative of this.

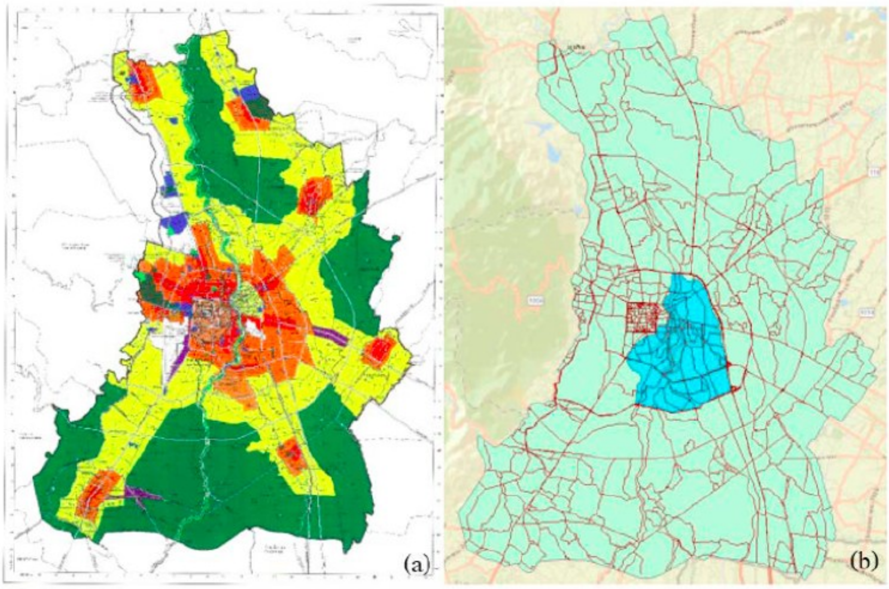


Figure 28. Extend of the urbanization of Chiang Mai in 2010 and the risk area of flooding in the inner city (modified from Department of Public Works and Town and Country Planning, 2010 in Tachaudomdach *et al.*, 2021). Urbanization has considerably increased since the publication of this map (McGrath *et al.*, 2017).

4.3. Consequences of Ping River flooding

While the suspended sediment in Ping water is around 500 mg/l during the rainy season, the load can considerably increase during flooding to 800-1500 mg/l at P.1. with estimations as high as 8000 mg/l in the initial flooding front (Wood & Ziegler, 2007). As major floods last several days, a significant quantity of these sediments is deposited in flooded areas with a granulometry that expectedly decreases with the distance from the main channel. During 2005 floods, fine sand was found within 50 m of the main channel where the flow is around 1.5 m/s; coarse silt (30-60 microns) 150 m from the river and fining away from it as the floodwaters lose their suspension abilities in calmer areas except around tributaries where turbulent flow can allow thicker and coarser sediment further inland. In terms of thickness, up to 15 cm of silty sand was found next to the river, 8 cm at 250 m from the main channel, 4 cm at 350 m and 0.5 cm at 450 m in the studied area (Wood & Ziegler, 2007). The average sediment deposition over the floodplain is 20 to 45% clay and the rest essentially a silt fraction with a content ranging between 67 to 83%. The average sediment deposit is around 33 kg/m^2 as a wet mud of density between 1.6 and 1.7 g/cm^3 (Wood & Ziegler, 2007, 2008) (Fig. 29; 42).

The high volumetric flow of water and the velocity of waters in the main channel are also responsible for significant erosion in some areas. Most river banks in rural areas are unprotected and while sedimentation can occur in the floodplain and as accretion in point bar deposits, in the outer parts of meanders or in mismanaged weirs, erosion can be substantial. Banks protected by concrete slabs or other techniques prevent erosion unless it fails, in which case erosion of the unprepared soft soil can be significant (Fig. 30a, b).

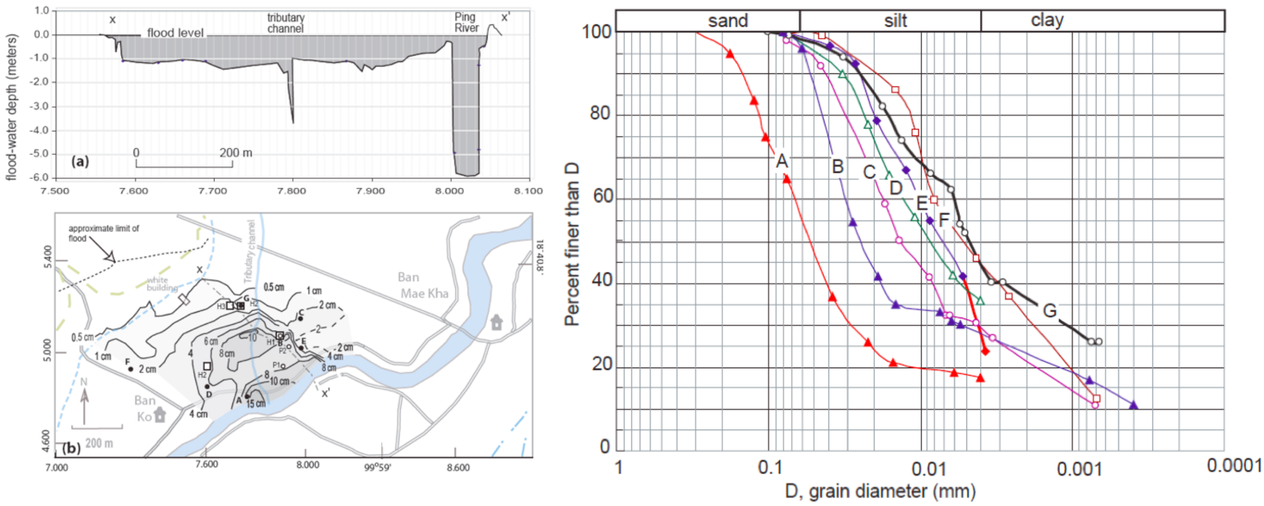


Figure 29. (a) Cross-section of Ping river and adjacent flood plain. (b) Isopach map showing the flood sediment thickness in the flooded area next to the Ping river. Right: Granulometric distribution of sediments collected in location labeled on map (b). (Modified from Wood & Ziegler, 2007; 2008)

Aside from erosion and sedimentation in the Ping river, it is worth noting that other types of flooding such as flash flooding in creeks and Ping tributaries in foothills areas, can be more extreme. The heavy rainfall on steep slopes can create a runoff that produce significant erosion and carry boulders of a few tens of centimeters if the source rock provides it (Fig. 30c). Some of these flash floodings, fortunately particularly in remote areas and rare near human settlements, have more similarities with debris flows and are obviously very destructive due to the high density and dynamic energy associated with it (Fig. 30d).

Aquifers are also at a higher risk of contamination during floods due to microorganisms, sewage, oils, agricultural & industrial wastes, chemicals, etc. Aquifers generally recharge through rainfall and direct infiltration but unless these are in floodwaters, there is no risk of contamination and in Chiang Mai such recharge zones are on the edge of the basin, far from the flood plain (Fig. 10). However, infiltration also occurs through waterways. The vadose zone overlying an unconfined aquifer stays undersaturated for several days at least, still providing plenty of time and space to filter contaminants in a very slow gravity-fed percolation process. However, if the wetting front of the flood progress downward to the water table, transfer of contaminants occurs more efficiently in a fully saturated system. To some extent, the same can occur for rising aquifers becoming unconfined. Despite all this, the highest risk pathway for local contamination of an aquifer is inadequate capping of wells in flooding areas, giving a direct access of flood waters into the aquifer with very hydraulic conductivity.

Figure 30. a. Loss of bank protection (concrete slab) and damage to a bridge in Mae Wang river; b. Loss of bank protection (wood piles), erosion and levee failure in Mae Wang river; c. Post flash flood (~4 hours) in Nam Hu river with large pebbles accumulation and record of water level in grassland. d. Debris flow in Hill 876 NE thalweg in Mae Wang (see Fig.23).

A more dramatic outcome of significant fluvial flooding is a major change in the main river channel called avulsion. River avulsion occurs when the streamflow breaches the normal channel and is diverted towards another trajectory, forming a new channel system that may or may not rejoin the parent channel downstream. It happens when the main channel is unstable and too inefficient to transport streamflow and sediment load. Flooding is the main natural cause for such event although earthquakes can be another mechanism aside from human interference (Teo, 2018). No avulsion occurred in the Ping river in living memory but it is a significant risk since the river has done it many times in the past, seemingly around 5 times in the past 500 years (see 5.3). Considering the significant rate of urbanization in the CML basin, avulsion is a potential worrying outcome as events in urban areas are generally catastrophic (Indus river in 2010; Kosi river in 2008; Yellow river in 1855). Efforts to control braided rivers such as the Ping river through dams, embankments or flood retention basins are effective solutions but this type of infrastructure can have all kinds of secondary impacts (Laonamsai *et al.*, 2023).

5. . Historical records & extreme events in the Upper Ping catchment

5.1. Generalities

Rivers occupy a special place in the traditional and spiritual (animist & Theravada buddhism) context of the early Mon and Thai kingdoms (Penth, 2004; Ng *et al.*, 2015) and is still visible today through major religious celebrations such as Loy Kratong and Songkran in which water plays a central role and the traditional belief towards Phra Mae KhongKha (mother river) (Jompakdee, 2004).

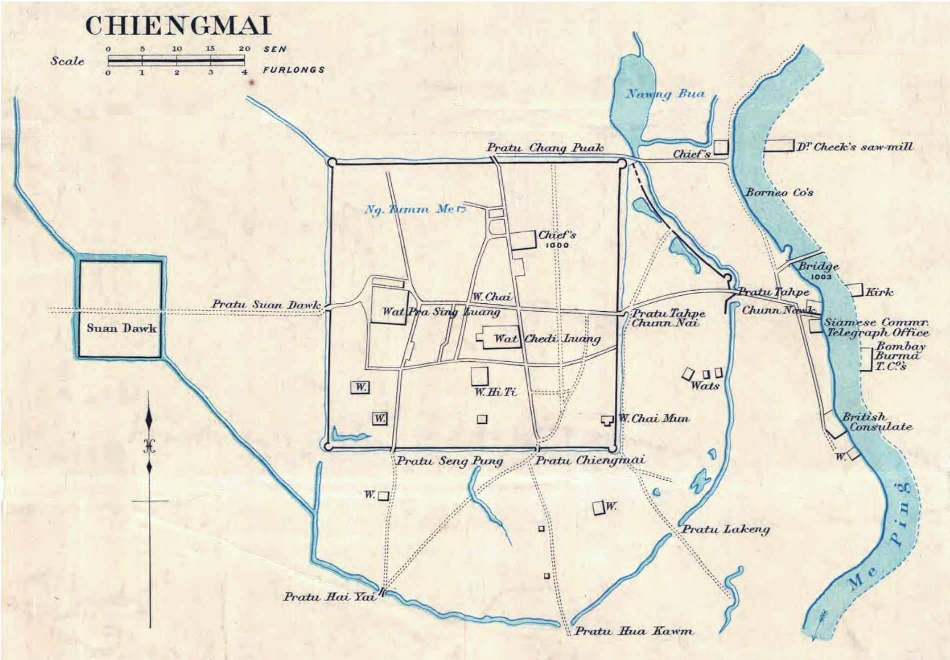


Figure 31. Map of Chiang Mai in 1888-1902 where the Ping river, moats around the city, Mae Kha canal and its connection to swamps and smaller canals are displayed (McCarthy, 1888).

In the early Lanna kingdoms (13^{th}-14^{th} century), capitals (Chiang Mai, Chiang Rai, Chiang Saen) were founded along main rivers to exploit water and use it for efficient transportation and as such, the Ping river was a key channel of communication towards southern cities such as Haripunchai and Sukhothai and later on Ayutthaya (Lebel *et al.*, 2009). Rivers were progressively tamed and disciplined for survival (cultivation, irrigation, transport, trade) and strategic (defense, communication) concerns and towns were established in the direct proximity of rivers, creating large wet-rice cultivating states with an extensive irrigation network (Ongsakul, 2005; Boomgaard, 2006; Teo, 2018). This network was fully developed in the late 13^{th} century into a series of laws, regulations and cooperation system between villages to manage the เหมือง-ฝาย (‘muang-fai, *tr.* canal-weir), a traditional irrigation system with a community-based infrastructure (Vichit -Vadakan, 1989; Ng *et al.*, 2015). The muang-fai system consists of weirs and channel diversions in a river (or main canal) made of bamboo stakes, logs, leaves and stones to bring water in a subordinate canal where irrigation water can be brought to rice paddies (na) through a system of sluice gate (tae) and rice field dikes (tang) (Mungsunti & Parton, 2017). Such infrastructure can be traced back to the Mon kingdom of Haripunchai (Sektheera & Thodey, 1974) and was replicated in the Lanna kingdom and later until the period between 1960 and 1990 when it was mostly replaced by concrete dams and larger canals run by the state (Lebel *et al.*, 2009). In some upland valleys, similar muang-fai irrigation practices can still be found, adopted by Lua and Karen ethnic groups for water management (Tan-kim Yong, 1983). In the Lanna kingdom, the traditional muang-fai in the CML basin presents itself as meandering planforms using paleochannels to conduct water while artificially constructed irrigation canals were generally more straight and angular (Teo, 2018). Around major urban centers, meandering loops were additionally used as defense or moats were dug and connected to the network of canals and rivers (Ng *et al.*, 2015) (Fig. 31).

In such context, seasonal flooding was a regular annual feature of the monsoon climate in flood plains of Thailand where most major cities (Chiang Mai, Lamphun (Ping), Lampang (Wang) Ayutthaya, Bangkok (Chao Praya), Sukhothai (Yom), Uttaradit, Nan (Nan), Chiang Rai & Chiang Saen (Kok & Mekong) have been founded for rice-growing civilizations (Manuta *et al.*, 2006). However, what is seen as a multi-faceted advantage can also lead to the abandonment of cities (Wiang Kum Kan), collapse of civilization (Angkor) or significant damage of ruins (Bagan) when the vulnerability of a river-based civilization cannot be or is no longer compensated by water management.

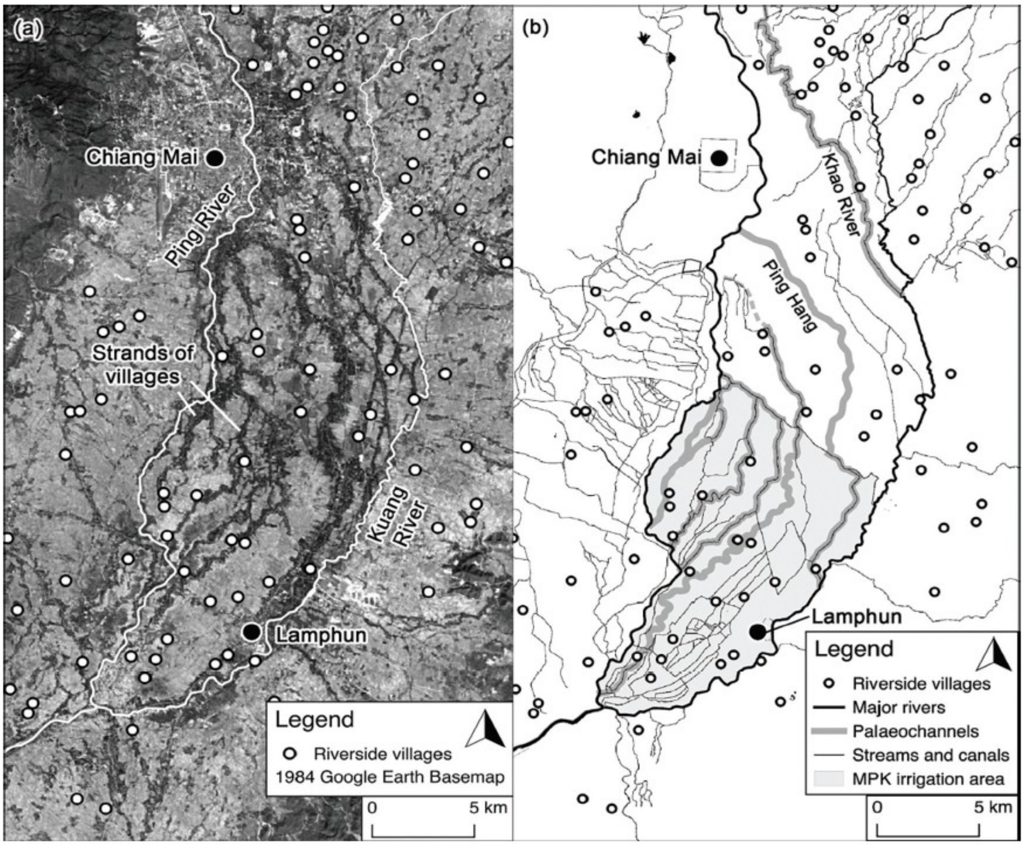


Figure 32. Satellite picture (left) and map (right) of the different paleochannels, canals and rivers as well as villages in the Chiang Mai – Lamphun basin (Teo, 2018)

Since minor flooding is an integral part of these cultures, Lanna architecture has traditionally a single story house on stilts higher than the mean annual flood level or floating houses attached permanently on a river or a canal (Nid, 1989) or villages build on natural levees where the higher ground protect from most flooding events (Teo, 2018). The pattern of settlement around Chiang Mai and the Lanna kingdom shows meandering strands and clusters of villages standing several meters above the paddy fields (now sometimes orchards) along rivers, streams and various water channels (still existing or buried) that are now mostly concealed by urbanization in the Chiang Mai metropolitan areas (Teo, 2018)(Fig. 32). Other than detailed topography, a remaining indicator is however visible in the toponomy of suburbs and villages such as the prefix สัน (‘san’) (i.e. San Patong, San Phisuea, San Phakwan, San Kamphaeng, San Sai, etc.) which means ridge or levee in the context of a floodplain while past Ping channels and irrigation channels through dry riverbeds are also present in the term เหมือง (‘muang’) (i.e. Muang Mae Ping Noi, Muang Mae Ping Kao, Mae Ping Hang, Muang Buak Khok, Muang Saen Yot,...) which stands for canal (not to be confused with เมือง (as in Muang Chiang Mai), which is historically a town with defensive walls and moats). These old canals and riverbeds are now filled and urbanised, starting with the development of the modern irrigation network in 1941 (Teo, 2018).

5.2. Timeline of various historical events

Below is an attempted timeline of water-related events in the past millenium in the CML Basin. Thai historiography had a strong tendency until the 1980s to neglect the description of rivers and floods for a nationalistic purpose of support to the legitimacy of the modern Thai state (Ng *et al.*, 2015). With that in mind, data available is mostly the reinterpretation of old texts, description in chronicles of Lanna cities ignored by Siamese historiography and recent archeological, hydrological and sedimentological data.

All years are expressed as common era.
768: Founding of Haripunchai on the banks of the Ping river (Swearer & Premchit, 1998) (See 5.3).
1277-1280: Earliest record of large scale water management: the excavation of the Ai Fa canal, a 36 km irrigation project (Teo, 2018).
1283-1284: Flooding in a place called Chiang Rua (Ng *et al.*, 2015).
1286-1287: Founding of Wiang Kum Kam on the western side of the Ping river, surrounded by a 4-side moat connected to the nearby river. An extra levee was also build along the Ping river (Ng *et al.*, 2015) (Fig. 33)(See 5.3).
1288: Wiang Kum Kam is established as the capital of Lanna on the western bank of the Ping River.
1288-1296: Wiang Kum Kam is flooded every year and ponded water and sediment deposition is too difficult to manage (Wyatt & Wichinenkeeo, 1995; Hinz *et al.*, 2010).
1293: Earliest historical date for the manufacture of the reclining buddha in the Haripunchai-built Wat Phra Non Nong Phueng temple. The reclining buddha (current one is likely from the 19th century) was originally build to have spiritual control of the water of the adjacent Ping river (Teo, 2018) (see 5.3).
1296: As a result of a decade of flooding, the capital is moved to Chiang Mai and Wiang Kum Kam remains a satellite village used for commerce, religion and defense outpost (Ng *et al.*, 2015; Teo, 2018).
1336-1355: Wat Pan Sao, ruins lying between Suan Dok & Ram Hospital, was built and later destroyed by a flood, covering it with 0.5 to 1.5 m of sediments and debris (Hinz *et al.*, 2010)
1300-1400: The Ping Hang is described and excavation work for a SW canal is done, possibly to reduce the flooding in Wiang Kum Kam (Teo, 2018) (see 5.3).
1411±12: Based on carbon-14 dating, this is the last date obtained for the artificial levee that was built to protect Wiang Kum Kam from the Ping river (Ng *et al.*, 2015).
1412-1552 is the range of years when the Ping Hang avulsion could have occurred.
1483±70 and **1477-1512** are respectively the optically-stimulated luminescence and carbon-14 datings of a coarse sandy layer present in the paleochannel north of Wiang Kum Kam.

1524-1525: Historical record of a catastrophic flood in Chiang Mai with many deaths at Siphum market (NE moat corner). It could be the date of the Ping Hang avulsion but there is no record of it (Ng *et al.*, 2015).
1545: Intense earthquake causing extensive damage to Maha Chedi Luang & Wat Phra Sing on the 28th of July (Ng *et al.*, 2015). Although improbable in this case, some avulsions are caused by seismic shifts and 1545 was a year with significant rainfall (Kazmer *et al.*, 2011).
1558: Prior to this date, but after ~1500, Wiang Kum Kam is abandoned based on archeological and architectural evidences showing no Burmese influence or mentions of the invasion (Teo, 2018).
1527-1831: Wat E-Kang in Wiang Kum Kam is buried under a massive layer of silt from a single flood (Velechovsky *et al.*, 1987). The area of Wiang Kum Kam is covered during that period by 1.5 to 1.8 m (Hinz *et al.*, 2010) of sediments coming from the N and NW (Ng *et al.*, 2015; Teo, 2018).
1774 or some years after: Wiang Kum Kam is resettled with no visible traces of the old city (Teo, 2018).
1831: Catastrophic floods with more than 2 m of water in the floodplain (Teo, 2018) and further avulsions (Wood & Ziegler, 2008).

5.3. Extreme events in historical and sedimentological records

The historical archives are not meticulous of the record of floods, droughts and major changes in the flood plain. However, the description of some historical events show that significant changes have occurred in the CML basin over the past thousand years.

In Lamphun, the description of the original founding of Haripunjaya in 768 on the western bank of the river Ping (Swearer & Premchit, 1998) clearly contrasts with the current situation where the Ping is 5 kilometers away, while an artificially dug Kuang river channel is passing on the eastern side of the old city.

In old texts, Wiang Kum Kam was described as founded in 1286-87 and lying on the western bank of the Ping river, a suitable place for settlement, surrounded by rice-bearing floodplains and easy access for trade and travel through the nearby Ping River (Ng *et al.*, 2015). It wasn’t until 1984 and the discovery of tablets buried at Wat Chang Kam that the ancient lost capital of Wiang Kum Kam was rediscovered on the ‘wrong’ eastern side of the Ping river, several hundred meters from the current river (Fig. 33).

Eventually, detailed studies of the archeological site revealed a paleo-channel passing just north of the site that is now called Ping Hang (Pitrakul & Uttamo, 1987; Velechovsky *et al.*, 1987; Hinz *et al.*, 2010). Ping Hang was the main Ping channel connecting Wiang Kum Kam to Lamphun, 23 kilometers away. It is now mostly dried up and filled or built but some present time urban structures are still associated with its path such as highway [106] (Old Chiang Mai – Lamphun Rd) which is a mildly meandering road sided by large Yang Na trees built on a 5 meters alluvial ridge that follow the current irrigation canal (Khlong Mae Ping Hang) in its southern part (Teo, 2018). In Wat Phra Non Nong Phueng, not far from highway [106], a Buddha statue was built in 1293 for protection from the nearby river, the Ping Hang that is only 150 meters away. The Ping river is now 3 km from the temple and its auspicious statue but during the great flood of 1952, when the Ping Hang was actively used by flood waters, the protection given by the Buddha was seen positively by the local population (Teo, 2018).

When Wiang Kum Kam was flooded, the amount and coarseness of the deposited sediment suggest that the final flood leading to the abandonment of the city would have been more destructive than the equivalent 2005, 2011 and 2024 floods (Ng *et al.*, 2015). It remains unclear exactly when such event took place. The excavation work done in the 14th century for a canal that would now pass where the current Ping is might have played a role. It is certain the final flood occurred before 1558 and despite floods rarely mentioned in archives and chronicles, 1524-1525 remains a likely date for this flood as it reached Chiang Mai old city (to the moat) with a catastrophic flooding up to Siphum.

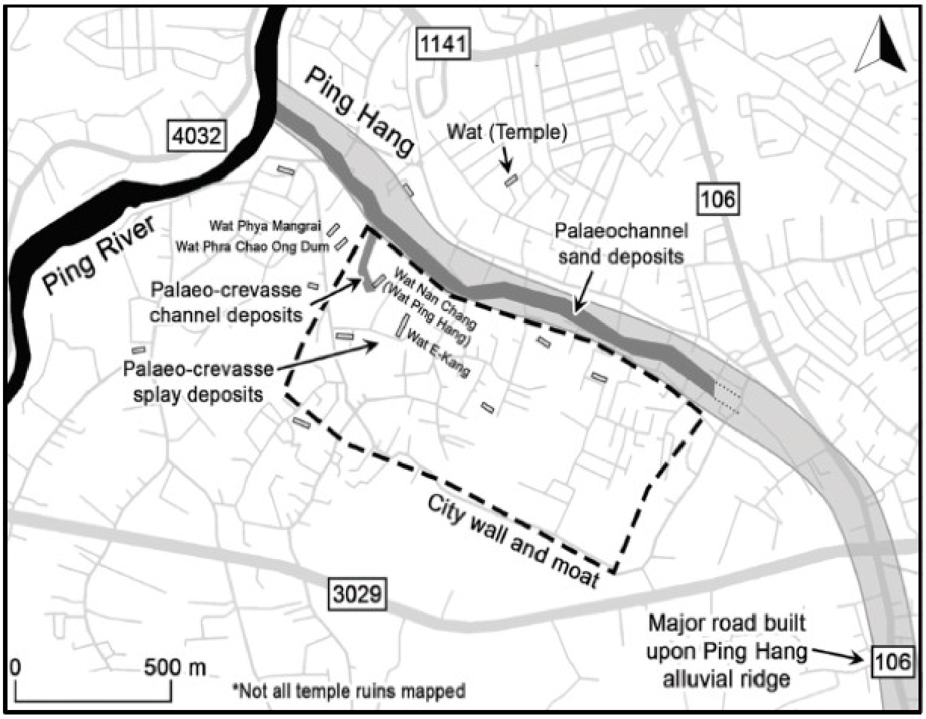


Figure 33. Palaeochannels and archeological discoveries in the Wiang Kum Kam area between the current Ping River and roads [3029] and [106] and the now buried Ping Hang (Teo, 2018).

Archeological evidences show that the area, built in the 14th century was mostly destroyed and covered with 0.5 to 1 m of sediment (Hinz *et al.*, 2010) and likely coincide with the abandonment of the Ping Hang river bed. There is some evidence that other paleochannels such as Muang Buak Khok, Muang Mae Ping Boi, Muang Saen Yot and Muang Lamphun are also abandoned channels that are younger than Ping Hang, indicating that avulsions in the past 500 years have a westward succession that might have started with Khao river (Teo, 2018) (Fig. 32, 34).

The Khao river is the westernmost identified paleochannel connecting the current Kuang river with a paleo-Ping river. The paleochannel is highly modified (canals, drainage, filling, etc.) but still exists as an irrigation canal 5 to 10 m wide in Mae Faek and Mae Nong Han alternating with some natural meanders 15-25 m wide to then disappear in the suburban environment in a series of 1-2 m wide canals. One of these drains is still named Khao river and ends 400 m from the current Kuang river. The Kuang river is now artificially diverted south but would have flowed SW in its alluvial fan and reached a confluence with the paleochannel of Khao river (Teo, 2018).

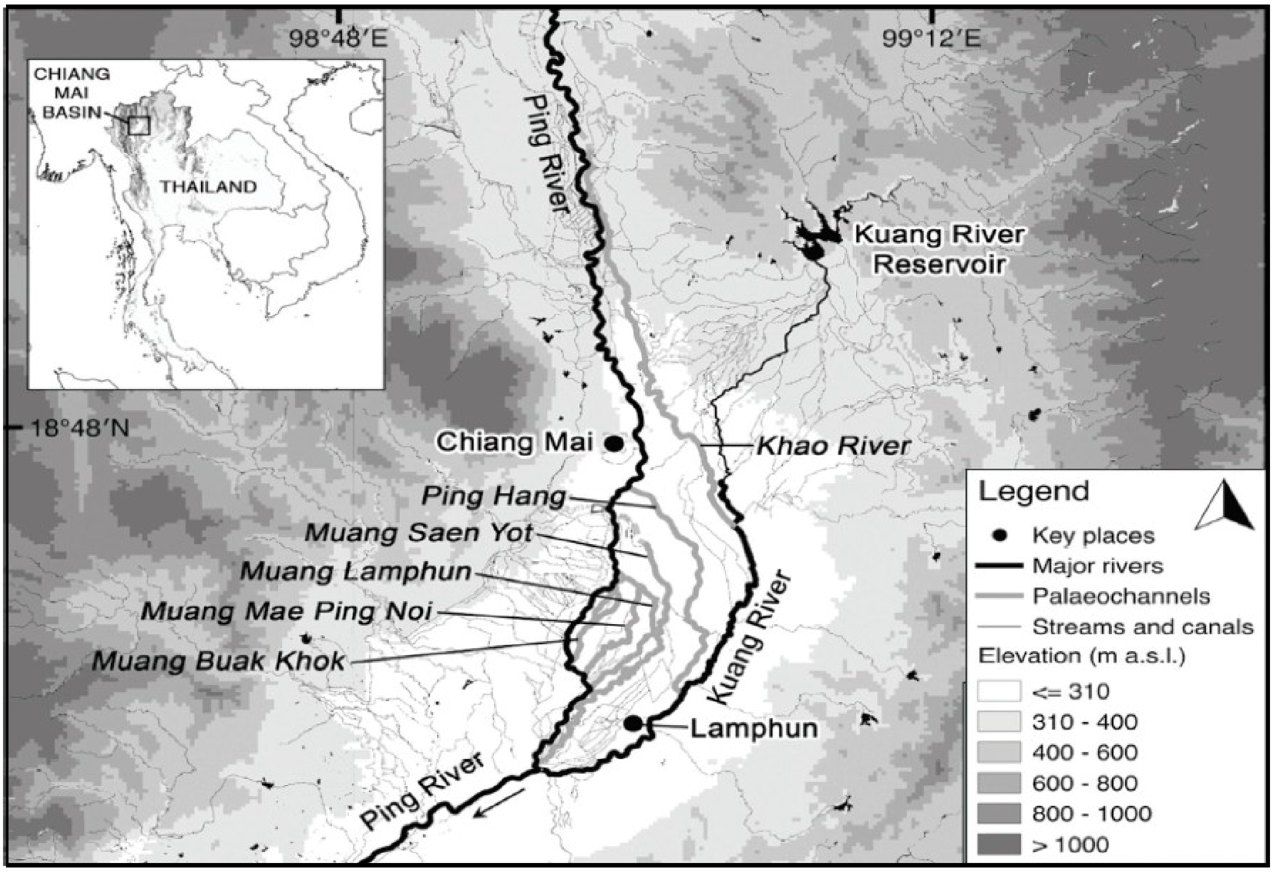


Figure 34: Identified paleochannels of the last millenium in the Chiang Mai – Lamphun basin (Teo, 2018).

This last paragraph is related to a main tributary of the Ping River, the Mae Chaem river in the western part of the catchment. In the CML basin, the Ping river has a wide floodplain with steep terraces. A drastic increase in flow volume during a major flood is not associated with a strong increase in inundated surface. Therefore, while the water depth can provide some information but poor resolution, the extent of the flooded surface in the basin does not give valuable information on very high river stages. Therefore, sedimentological, archeological or historical records of extreme peak flows during floods might not be identified. By contrast, in a smaller watershed and/or with a narrow to absent flood plain, there is a high and robust correlation coefficient between rainfall, rainfall rate and flood characteristics. For medium size watersheds like Mae Chaem or the uppermost Ping, interannual changes of the river bed and valley are minimal despite variable rainfall (Kuraji *et al.*, 2007) and extreme flooding events are more accurately recorded. The Mae Chaem river has a section where the river bed pass through a steep bedrock-confined channel where a constant historical cross section can be assumed due to limited erosion or deposition and a very high vertical accuracy on extreme river stages in the slot canyon of Ob Luang. In such a situation, flood water levels can be directly calculated into peak flow volumes and with additional research on deposited material, can provide an estimation of major palaeofloods and return periods.

The Mae Chaem is a 3853 km^2 basin ranging from Doi Inthanon to 273 m where it reaches Doi Tao Lake (Vongtanaboon *et al.*, 2008). Some of the flooding history is recorded in documents and human activities but also in situations where sediments and debris such as trees are accumulated in perched caves on the sides of narrow canyons. Timber logs lodged in gorge caves and silt & sand in slackwater deposits (along main channels and gullies) can be dated (Kidson *et al.*, 2003). Results show that the average annual peak discharge for 1953-2001 data is 421.8 m^3/s which is not fundamentally different from the Ping river average peak flow in Chiang Mai. In 2001, a large flood passed through Hot on the 13th of July at 4 am, reaching +7.98 m above the river bed with an estimated volume flow of 794 m^3/s (Vongtanaboon *et al.*, 2008), again, similar to the large floods that the Ping river can produce. Earlier records show that the significant flood of 1960, that was measured as 1030 m^3/s, is calculated with currently preserved sedimentological evidence as 980 m^3/s (Kidson *et al.*, 2003). With this simple relationship established and validated between terrace and cave deposits and peak flow, it became clear that some time around 1900, an extreme flood has occurred, carrying wood debris and depositing sand terraces so high in the narrow flood plain and canyon that a volumetric flow of 2420 m^3/s is inferred. The carbon-14 age estimation based on tree logs gives 125±40 and 110±40 BP and archeological artifacts of logging activities in flood debris give a high probability for the 1889-1908 interval. The younger age limit of this very significant flood is a downstream temple that was destroyed and rebuilt in 1924. That such extreme flood (2.4 times larger than the largest directly recorded flood) can occur in recent times leave some doubt on what extremes are achievable in the Ping river as it passes through the CML basin. Such situation is explored in section 7.2.3.

6. Human activities, flooding & drought consequences and human responses

6.1. Human activities in the Ping basin

6.1.1. Infrastructure timeline

For the past 70 years, the Thai government has been in the process of replacing the traditional water management of muang-fai into more modern, robust and efficient infrastructure. It started in 1938 with the People's Irrigation Act which was one of the first major water policy in modern Thailand. The law recognised the role of local communities in managing irrigation systems, usage and maintenance. In Northern Thailand, it provided some legal framework for the widespread existing muang-fai infrastructure. Over the years since this government act, the RID has attempted to organize farmers and rural communities into groups and associations to provide a wider scope to water management but it systematically collapsed due to the lack of community support as it left inadequate scope for local management decisions (Molle, 2007). Eventually, most local involvement has been supplanted by modernised weir and dam systems managed almost independently by the RID.

In 1950, following a successful application to a World Bank loan, a 25-year irrigation development program was initiated in 1952, starting with the Chao Praya (Chao Praya dam (1957)) but quickly followed by a series of 5-year plans in the 60s to the 80s with notably the building of the Bhumibol dam (1964), then Kiew Lom Dam (1968) and Sirikit Dam (1974) as well as other lesser barrages and canals such as the lower Mae Ping dams in Kamphaeng Phet and Nakhon Sawan (1991), etc., and the Upper Ping Weir Project in Chiang Mai (Lebel *et al.*, 2009, Bidorn *et al.*, 2016; Chaiwongsaen, 2018). These systems were very efficient to regulate water variations downstream and prevent annual minor flooding. While prior to the Bhumibol dam construction, the lower Ping had a water level variability in the 1000s of m^3/s in Tak, the average peak runoff is now 240 m^3/s with variation around 300±200 m^3/s (Fig. 35)(Bidorn *et al.*, 2016).

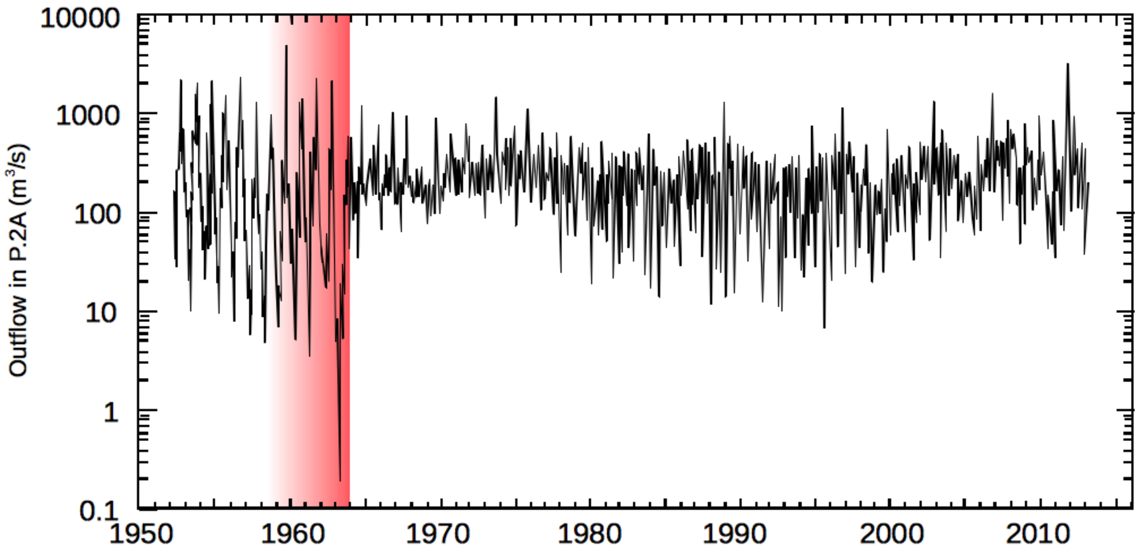


Figure 35. River flow variation downstream in Tak, before (<1964) and after (>1964) the construction of Bhumibol Dam across the Ping River. The Bangkok floods of 2011 are visible as a spike on the right side of the diagram (modified from Bidorn et al., 2016)

The 1952-1977 water management program of the Chao Praya basin is part of a set of policies designed to intensify agriculture through multiple cropping in the dry season and created a legal framework for state control of water using physical infrastructure (Lebel *et al.*, 2009). The initial systems were mostly seen as a management of the upper part of the Chao Phraya catchment (including most of the Ping river) for the benefit of the Central Plains downstream. In that early phase, the effect of the consequences of building such important infrastructures like the Bhumibol dam on the upstream section of the Ping river were neglected. As a result, the base level of the Ping river at Bhumibol dam was raised by ~100m, filling Bhumibol basin into a lake, flooding the gorge between that lake and the lower part of the CML Basin forming Doi Tao Lake. This drastic modification of the base level of the Ping river just downstream of an intermontane basin created changes in terms of sedimentation and flooding in Chiang Mai (Fig. 36). The natural Ping river system shows headwaters arriving in a zone of significant gradient loss, causing the river to naturally widens and meanders. To some extent, the current channelised and narrow Ping river receiving extensive water discharge from tributaries during floods should still favors sediment transport over sediment load (Chaiwongsaen, n.d.). However, the presence of Doi Tao-Bhumibol Reservoir considerably change the equilibrium profile and promote sedimentation upstream of the lake, causing extensive deposition and aggregation of sediment in point bars, and higher probabilities of flooding (Chaiwongsaen, n.d.). These issues caused by infrastructure downstream of Chiang Mai required channel modification in the CML basin. Between 1970 and 2007, the conveyance factor of the Ping river was therefore increased by 7% in P.67 and 3% in P.1 through renovation of flood defenses, dredging and excavation of the river bed (Chaipimonplin, 2010). However, this situation requires annual maintenance and partly explain why the largest flood in recent time (2005) had a lower river stage than floods with smaller peak flows (2011, 2024) when conveyance is lower due to some neglect in the maintenance of the channel ways.

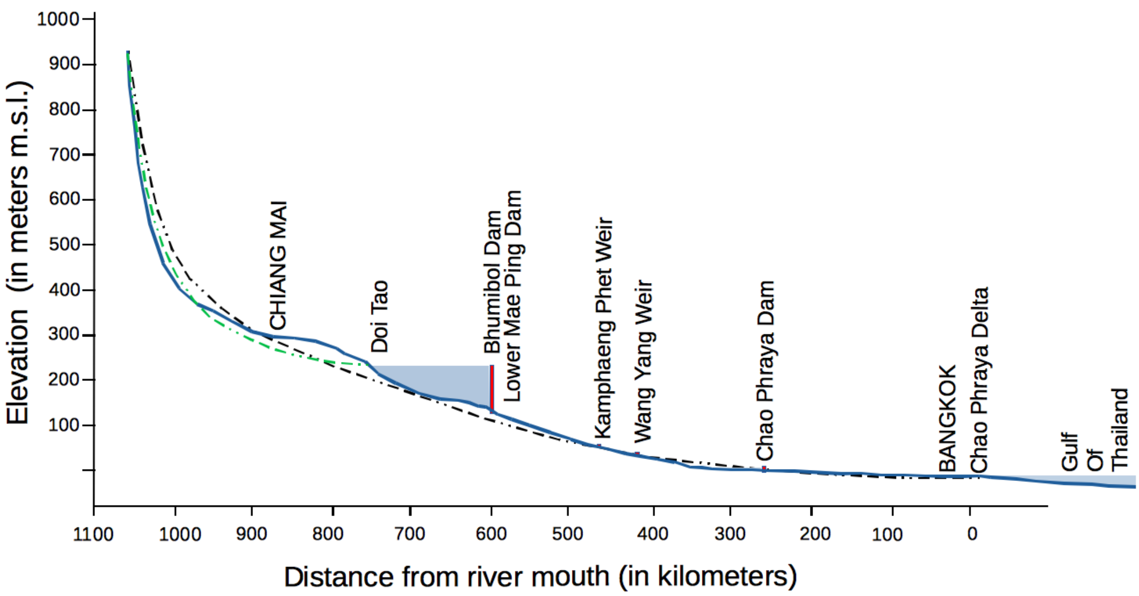


Figure 36. Equilibrium profile of Ping-Chao Phraya river system. The current river bed elevation is given in the continuous blue line. The dashed black line is the equlibrium profile before the construction of the Bhumibol dam while the green line is the new equlibrium profile created upstream of Bhumibol-Doi Tao lake (inspired from Chaiwongsaen *et al.*, 2019)

In the Chiang Mai – Lamphun basin, river flow regulation of the Ping river through weirs has been done extensively for the past half century, starting with Pa Ya Kam Weir (1925), Mae Faek Weir (1936), Mae Ping Gao Weir (1941) and then all weirs associated with the Upper Ping project such as Tha Wang Tan Weir (1980), Doi Noi Weir (1987), Pa Ya Utt Weir (1989), Wang Pam Weir (1990), Sob Rong Weir (1993), etc. (Fig. 37) To these weirs were added reservoir dams and conduits (i.e.: Mae Taeng Weir; Mae Ngat Dam (1985); Mae Kuang Dam (1991)) for flood & drought control. The initial strategy behind the building of these reservoirs was to reach capacity at the end of the rainy season to maximize water availability in the dry season and release water all year long to produce a usable base flow. The Mae Kuang Dam itself has been a recurrent project since a large flood in the area in 1886 but only achieved a permanent dam in 1935, eventually replaced by a rock dam in 1948 then 1991 with its present concrete dam structure. The Mae Taeng Weir was also an early project to respond for water shortage in the uppermost Ping zone. The Mae Ngat dam was designed for irrigation purposes and mitigate the floods in the city with a claimed capacity to control 30% of flood flows passing through Chiang Mai.

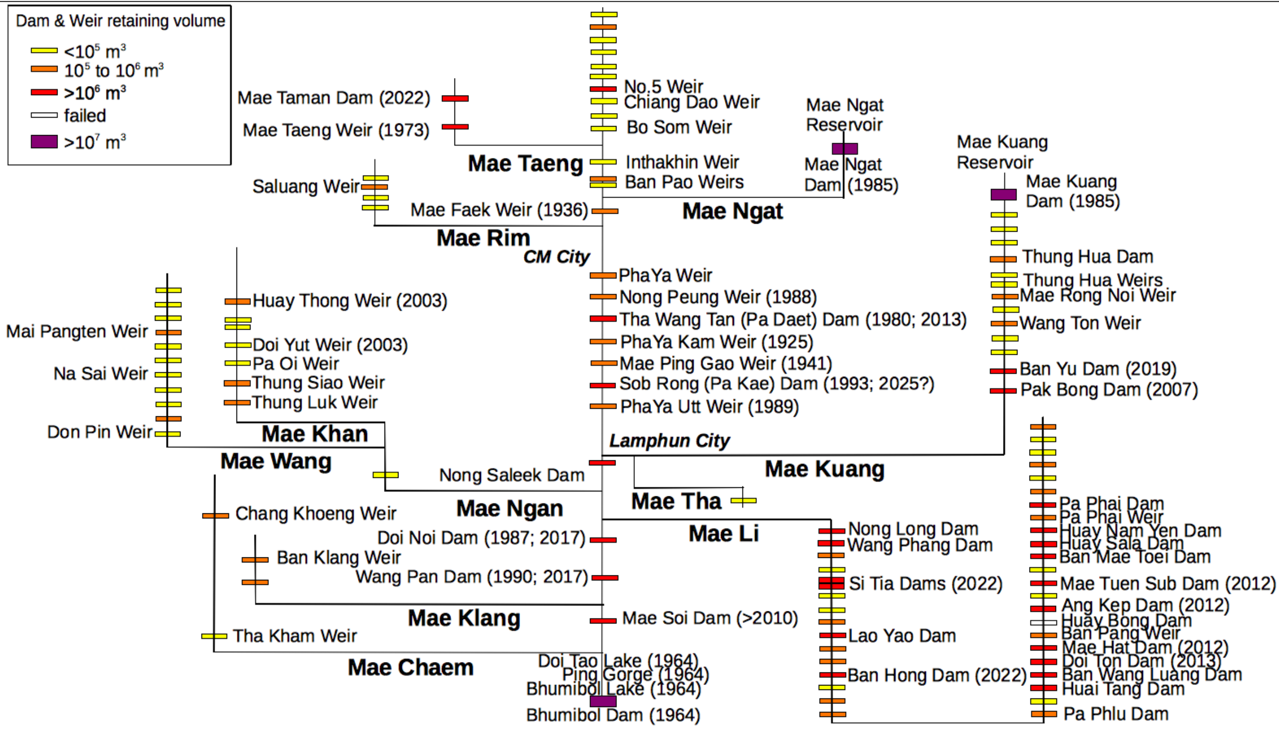


Figure 37. Schematic representation of main dams and weirs in the Upper Ping catchment and their year (when known) of construction and/or renovation.

Following the catastrophic floods of 2005 in Chiang Mai, the RID expressed its opinion that encroachment on the Ping river was excessive and the river was too narrow in many places, and numerous weirs that prevented the water to flow freely, conducing to floods. The RID designed plans to replace weirs with water gates as an ideal solution to retain flow in the dry season and permit free flow when needed in the wet season (Lebel *et al.*, 2009). As a consequence, some weirs were left in disrepair (Chang Klang Weir, Nong Hoi Weir) and other were upgraded to flood gates (e.g. Tha Wang Tan Weir in 2013). Following the very high floods of 2024, the removal of additional weirs (maintained or degraded) is again being discussed to improve the conveyance factor of the Ping river during floods.

After 2005 floods, the RID, along with the HWMC have been allocated 13 billion baht for long term improvement of water ways in the Upper Ping, including better monitoring of rivers, improved warning system and flood preparation, the building of larger dykes and weir-levelling projects but for the latter, the opposition by local communities has prevented the full applications of these improvements (Lebel *et al.*, 2009)

Upstream of Chiang Mai, 2005 floods also initiated a serious discussion on the Mae Ngat-Mae Kuang-Mae Taeng diversion tunnel project (Sutiwanich *et al.*, 2006). This large project was eventually started in 2015 and still under construction. The Mae Kuang Udomthara Reservoir Project was started with the Mae Taeng – Mae Ngat diversion tunnel, connecting the two areas with a 4.2 m diameter, 22.975 km long tunnel and the Mae Ngat – Mae Kuang diversion tunnel connecting the two lakes with a 4 m, 25.401 km long tunnel. Once finished, it will allow to distribute the water from the Mae Ngat reservoir to the other two water systems, with outlets in the Mae Kuang and the Mae Taeng and Canal Road flowing in the western part of Chiang Mai (Fig. 38).

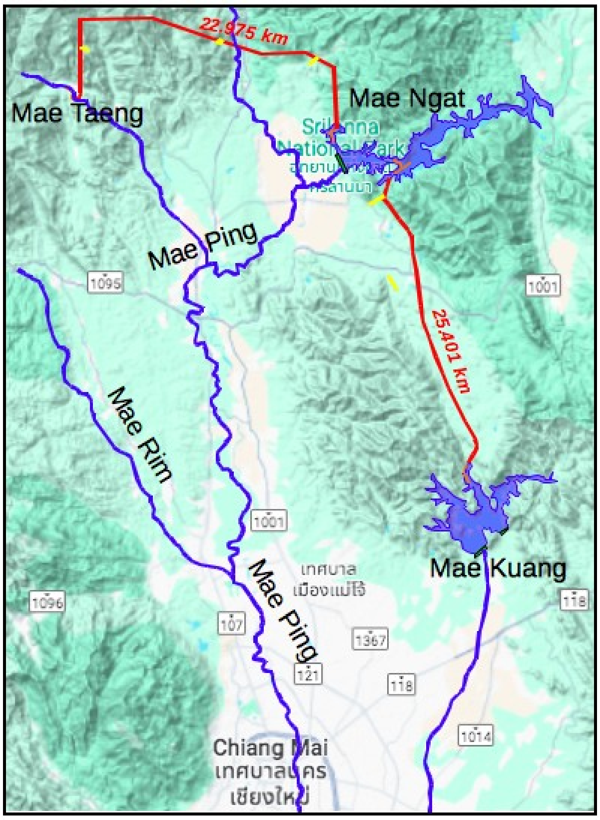


Figure 38. Simplified map of the Mae Kuang Udomthara Reservoir Project with main rivers and reservoirs

Aside from dams & weirs, channels and irrigation have also significantly affected the Ping basin. Since the 1960s, the Upper Ping has been transformed with significant expansion and intensification of agriculture, urban-industrial growth and tourism (Rigg & Nattapoolwat, 2001) and more recently, a shift from forest exploitation to conservation and upland watershed management (Lebel *et al.*, 2009). One resulting effect is that in the past 50 years, the inflow into Doi Tao Lake (and Bhumibol dam) has decreased by 0.47% per year (Sharma *et al.*, 2007) due to irrigation that has been greatly expanded with forests converted into orchards, croplands and urban areas.

In Chiang Mai, the inflow is in a decline that average around 0.28% (3.3 mm) per year (Lebel *et al.*, 2007) and a similar trend is observed in Lamphun since the establishment of the industrial estate during the 1977-1981 with significant infrastructures built by the RID to replace the existing muang-fai system (Lebel *et al.*, 2009). It is estimated that between 1972 and 2005, the irrigable surface in the basin has increased from 500 km^2 to 2140 km^2, with around 70% managed by government agencies and the remainder by a variety of local communal systems. This significant change over a few decades brings an annual challenge in operating water infrastructure upstream to balance flooding prevention with maximum storage for the dry season (Tan-Kim Yong *et al.*, 2005; Lebel *et al.*, 2009).

6.1.2. Land use modification

Forested areas

The current land use in the Ping catchment consists of forested areas (dry dipterocarp, dry evergreen, hill evergreen, mixed deciduous, pine, bamboo, secondary regrowth forests), plantations (pine, eucalyptus, teak, orchards), grassland & savannah, rice paddies, water bodies and urban areas (World Bank, 2006).

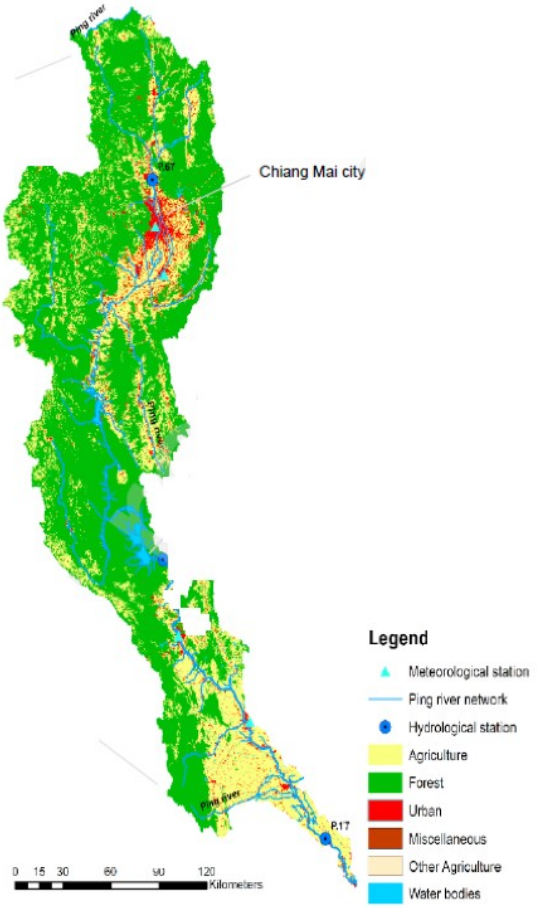


Figure 39. Land use in the Ping river basin (Chapagain *et al.*, 2025)

Naturally forested areas have changed extensively in the past decades. Primary forest is supposed to have covered 100% of the region prior to Haripunchai-Lanna period and has marginally decreased during that time (Walker, 2002; Sriwongsitanon & Taesombat, 2011; Lim & Boochabun, 2012) until the second part of the Rattanakosin period where some more commercial deforestation occurred. In 1960, the forest cover represented 70% of Northern Thailand while in 1998, only 43% is forested (Charuppat, 1998; Walker, 2002; Thomas *et al.*, 2002; Wood & Ziegler, 2008) (Fig.39). The Ping catchment itself is less dramatically affected by the deforestation campaigns of the 1960s to 1989, when the logging ban was introduced and decreased from 83% in 1973 to 67% in 2005 (Lim *et al.*, 2012). Between 1990 and 2009, forest land use has increased over the Ping catchment by 2.1%, with up to 3.5% increase in the Upper Ping catchment (Reda *et al.*, 2014). This is mostly secondary forests and only steep and remote areas have kept their original canopied forest of tall trees (Wood & Ziegler, 2008) (Fig. 40).

The role of forests in water management is often partly misunderstood and exaggerated. Deforestation plays a role in increased localized streamflow due to decreased interception, evapotranspiration and reduced soil infiltration (Cuo *et al.*, 2008). It results in some effect on peak flow, particularly in flash flooding, but a closer investigation shows that it is not as supported by research for river floods as the general public think (Bruijnzeel, 2004; Bradshaw *et al.*, 2007; Forsyth & Walker, 2008). The observed trends in the Ping catchment from the 16% of forest loss in recent times do not seem to produce a significant change in stream flow or rainfall when all variables are considered (Alford, 1992; Wilk *et al.*, 2001, Walker, 2002, 2003; Bruijnzeel, 2004; Lim *et al.*, 2012) and it remains an evidence that floods are triggered by intense rainfall events, with or without the presence of forests (Sriwongsitanon & Taesombat, 2011).

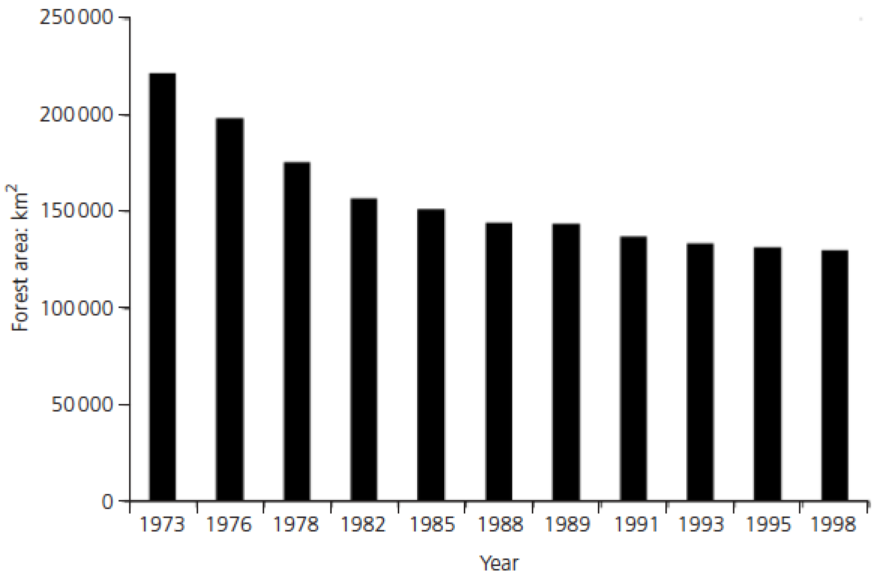


Figure 40. Evolution of the forest cover in the upper Ping since 1960s (Ekkawatpanit *et al.*, 2013)

On the other hand, it appears that since evapotranspiration of forested areas return 80% of rainfall to the atmosphere, in some low slope areas, a reduced forest cover can lead to additional infiltration and higher dry season base flow (Walker, 2003) and possibly have a positive resulting effect for drought conditions. In a higher slope system, the replacement of forest with terraced rice paddies probably slows, filters and absorb more water than any other equivalent land use on such topographical feature (Walker, 2003). However, in the Upper Ping, agricultural land has increased by 15% since the mid-20th century but not significantly between 1990 and 2009 and no additional changes in rainfall absorption is expected in that time period. In the lower and middle Ping, a continuous increase in agricultural land is present (Lim *et al.*, 2012; Reda *et al.*, 2014). Overall, while some land can have higher water infiltration, new agricultural areas also leave less topsoil and a lower retaining water ability (Komsai *et al.*, 2016).

Roads

The widespread development of the road network also has significant effect on storm flows (Lim *et al.*, 2012). While surface runoff is normally quite limited in agricultural lands for the heaviest rainfall, overland flows can occur for almost every single storm on roads (Ziegler *et al.*, 2001). The effect of roads tend to be neglected when compared to forest and agriculture land use (Cuo *et al.*, 2008). Since many hillsides have clearing with numerous trails and roads (Wood & Ziegler, 2008), these barren surfaces provide a significant channeling effect for the runoff from rainfall.

The runoff into the floodplain and urban Chiang Mai is also accentuated by roads as it creates insufficient alternative drainage, creating water conduits through non-natural areas (Hui Yian Lee *et al.*, 2024) and in the city centre, where the narrow Ping is heavily channelized, the presence of bridges locally restricts the flow of water by producing even narrower and shallower zones in the direct vicinity of bridge foundations (Kumcumphet, 2007; Tachaudmondach *et al.*, 2021). Outside the city, various types of dams, weirs, channels and fluvial mining of sand result in significant changes in erosion patterns and deposition (Laonamsai *et al.*, 2023) that can have variable influence in flood conditions.

Urban areas

Urban planning is another major issue in flood management. The conventional approach in Thailand is a centralised process relying on decision of urban planners based on national regulations and policies. In practice, it is largely ineffective since this type of planning is done without consultation with local residents, investors and specific local conditions that would cause such planning to fail. Therefore, planned zoning is often directly challenged by local people and external investors and overall, mostly ignored (Chatchawan, 2005; Sangawongse *et al.*, 2021). As a result, Chiang Mai has grown substantially with a replacement of farmland into urbanised zones from 9% in 1989 to 33% in 2009 (Sangawongse, 2006; Lebel *et al.*, 2009; Sangawongse *et al.*, 2011) in a semi-erratic way with construction near the Ping banks and direct flood plains, changing flood conditions and possibly causing higher water levels (Lim *et al.*, 2012).

While the irrigation planning for the dry season (and flood management) was the initial motive for the large infrastructure projects, leading allocations, limitations, fees and maintenance applied to farmers for water usage, it has now been highjacked by economic development and the urban-industrial use of water for factories, hotels & resorts, golf courses, housing estates, army camps, university campuses and government institutions. These unexpected users (as least in the centralised planning concept) consumed very significant water resources with no requirements and no control at a time when it was not legally possible or defined by planning regulations. Policies to regulate these consumers are made a posteriori, as a fait-accompli even when it is detrimental to the water resources. The same applies to housing estates and industrial areas established on raised floodplain and surrounded by long flood protection walls, redirecting irrigation and flood waters towards areas where no plan exist to manage waters. Policies were set afterwards with no requirement on drainage necessities (Lebel *et al.*, 2009). While minor flooding were recurring but eventless situations in the past, it can now create new damage as flood risk is shifted elsewhere, caused by floodplain development in high risk areas with unsanctioned dykes and diversions (Lebel *et al.*, 2007).

6.2. Human response to floods

Floods & droughts are common occurrences in the Upper Ping and South East Asia as a whole. Communities have lived for centuries with seasonal floods appearing during the wet monsoon. However, in the last few decades, there is a growing perception that floods are a hazard that need to be controlled with the public opinion towards a perception of increase in magnitude and frequency due to climate change, deforestation, urbanization and population growth (Manuta & Lebel, 2005; Forsyth & Walker, 2008; Lebel *et al.*, 2009; van Dijk *et al.*, 2009).

In the last two decades, flooding has been a significant hazard in the Upper Ping river, causing extensive economic losses due to inundated farmland, reduction of commercial activities and residential damage. Direct loss from flooding covers areas in contact with floodwaters such as buildings, harvests, farm animals, cars and transportation, but also costs in lives & injuries, harm to cultural sites and biological destruction while some indirect losses and costs are due to the temporary halt of income for businesses and trade, industrial disruption, ecological loss, transportation disruption, legal costs of lawsuits, stress & anxiety, loss of community and ecological resources, etc. (Tachaudomdach *et al.*, 2021).

6.2.1. Pre-flood situations

Prior to a flooding event, warning data is available from upstream station P.67, providing 6 to 7 hours of reliable forecast on the arrival, progression and peak level of a flood with good accuracy (Fig. 18). Such warning is in place for the last 3 decades and information is provided through various media channels for urban areas and villages such as local broadcasting speakers and village meetings (Junkhiwaw *et al.*, 2004; Jarungrattanapong & Manasboonphempool, 2010) and more recently, social media. In mid-August 2005, despite an early flood watch warning 24 hours in advance, the 6-7h imminent warning and the availability of flood-risk maps of downtown Chiang Mai, the lack of education relative to floods, the absence of major floods for more than a decade and the assumption that the government project of river expansion, dredging and flood protection was adequate, lead the population to largely ignore the official warning. When the mid-August peak flow hit Chiang Mai, the population was mostly unprepared and unaware of the risks (Garden, 2007; Jarungrattanapong & Manasboonphempool, 2010, 2011) leading to extensive damage and unfortunately, several fatalities. The following floods and particularly the September peak flow met a more prepared population that took some preventive action when warnings were issued. Floods in 2011, 2022 and 2024 did not meet the level of unpreparedness seen in 2005. However, specific flood conditions and inadequate resources are still an issue such as the limited evacuation of 2011 due to peak flow occurring at night time (Komsai *et al.*, 2016) and the lack of coordinated flood management and information, causing difficulties in decision-making by the local government towards mitigation of the flood situation and transportation issues (Tachuadomdach *et al.*, 2021).

An increasingly new issue that appeared in the last decades is that despite the easier access to information, warning of an incoming flood and many updates on the ground situation, social media is also a tool that spread significant misinformation (or possibly disinformation) by propagating false claims on various type of ineffective flood protections or a focused attention on the inability of local authorities to manage the situation, which can lead to wasted time for efficient flood preparation and community help. Another concerning aspect is the social media interest in extraordinary, excessive and anxiogenic but false claims, that are particularly widely distributed when under a false argument of authority (Fig. 41).

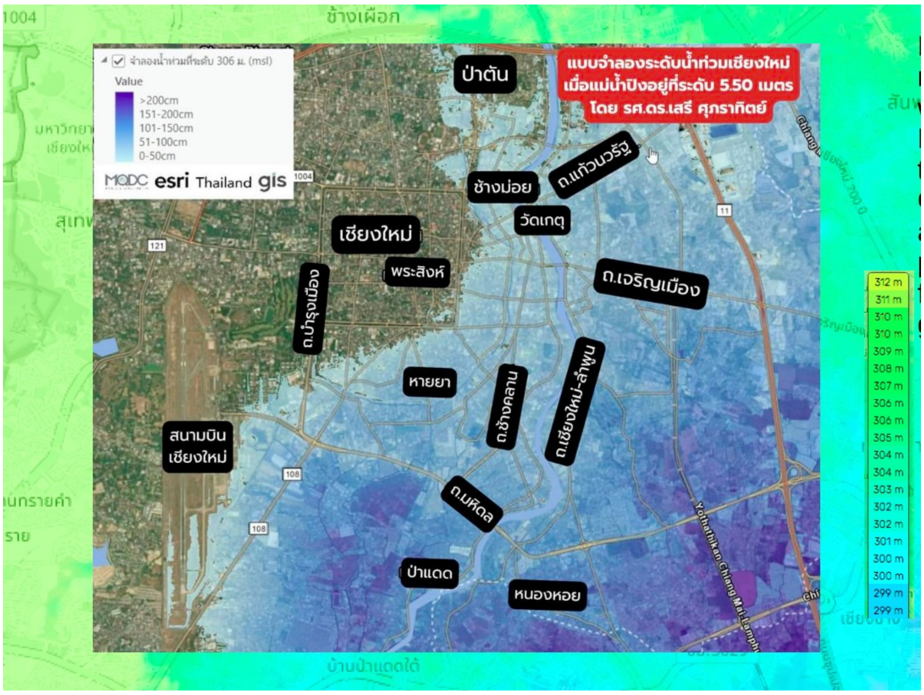


Figure 41. Modifed map of an abundantly shared social media post in 2024 providing a supposed model of a +5.5 m flood in Chiang Mai. Despite coming from an academic researcher, the map is very misleading as it bears no ressemblance with the numerous published models of floods in the area. As far as we can tell, The map is essentially a flood map if the sea level rose by +311 m (lime green) (or if Doi Tao Lake rose by 70 m). This piece of disinformation, supported by an argument of authority from a researcher who has no credentials to do so, led to significant anxiety among the population.

6.2.2. Flood perception, preparation and effects

Social studies on residents affected by floods show that rural homes, facing recurrent floods and being traditionally used to it, are overall more prepared than urban households in terms of adaptive strategies and are in general, a lot more autonomous. For both populations, the main limitation to preparedness and adaptation is financial, along with access to information during flood events, perception of these disasters and timing.

A significant difference between these two groups is the reliance of the urban population on public flood protection measures, which deter many households to take precautionary action on their own. With flood warning taken more seriously since the 2005 floods, 87.5% of residents in risk zones now consider moving belonging to higher ground, 70% of the at-risk urban population requests sand bags to build dikes with 30% wishing for more sand bags and 18% for more concrete blocks to build additional dikes (Jarungrattanapong & Manasboonphempool, 2011).

Despite preparation in minimizing damage and protection from floodwaters, damage to property is common and can hardly be prevented in some cases without significant financial investment. In rural areas, the damage to houses is generally less significant than urban households but agricultural fields are heavily affected, particularly vegetable farms. In standard houses, typical critical levels of damage are +0.4 m of water level that render sanitation unusable, +0.7 to +0.9 m often makes electricity unusable and +1.4 m requires 85% of residents in low income areas to evacuate. These low income settlements also have extensive damage such as swell, warp and decay of surfaces and walls even for water level below +0.4 m (Tikul, 2018).

Modeling of a major river flood (higher than +4.7 m) shows that around 6.33% of the Chiang Mai province population is affected. Following the 2005 floods, significant damage was observed on 2000 houses in the urban area as well as 179 roads and 87 bridges in the province. The number of affected persons is however larger since flooding affects particularly important districts for the economy, trading, education, healthcare and transportation with 21 schools (>50000 students), 1 hospital (400 in-patient, 5000 daily out-patient) and a main bus terminal flooded in 2005 and 2011 (Tachaudomdach *et al.*, 2021). The 2024 floods with a river stage above 4.9 m showed that a second major hospital was included, several more schools, the Chiang Mai train station and numerous access roads (Fig. 42a, c, d).

Figure 42. a. Aerial picture of Chiang Mai city centre in the 2024 floods (source unknown); b. Post-2024 flood clean up (Thai Royal Army); c. Aerial picture of Chiang Mai train station in the 2024 floods (source unknown); d. Chiang Mai bus station during the 2005 floods (Chaipimonplin, 2010)

6.2.3. Post flood damage & effects

The amount of damage (as sum of property damage, agricultural output, health loss, forgone income, etc.) suffered by a household is obviously directly dependent on the level of flooding occurring in an area. However, for a same flooding level, there are a few predetermined factors that have an impact on the amount of damage. Prior experience and awareness of vulnerability is a very important factor that can in theory be enhanced through disaster training and preparedness but such programs are mostly inadequate in Thailand, therefore providing limited help. Adaptive behaviour is another important factor when dealing with warning time, rising waters and evacuation decisions to protect a household and its inhabitants from flood. Interestingly, collective adaptation through social organization with the building of flood protections in public areas has seemingly no effect on the damage occurred. The use of all available information channels did not seem to have a significant effect two decades ago but the situation can change from one flood to another and access to frequently updated online information has significantly increased since then. A fatalist attitude or perception of future severity lead generally to more losses than victims that keep trying to do something about it (Jarungrattanapong & Manasboonphempool, 2011).

Additional proportional effects also exist such as the level of income. Higher income is partly correlated with higher education and the relative damage is less important for this social group (9.7% of monthly income) than poorer social classes (54.2% of monthly income). However, in absolute financial loss, higher income that correlates with middle age and mildly old households, incurred more damage while young people, elderly and poor people have less possessions. The type of property also has an impact and farmland and single-level houses have higher loss (Jarungrattanapong & Manasboonphempool, 2011). Households experiencing complete loss are represented at 80% by poor households (less than 100000 THB/year), often in the non-Thai population living in flood prone areas (Tikul, 2018).

Health issues are reported in post-flood surveys and show that 20% of the population suffer of skin infections, fungal feet infections as well as some chronic dizziness and diarrhea (Jarungrattanapong & Manasboonphempool, 2011). Post-flood dried mud covering busy streets also created a significant amount of dust in the 2024 post-flood recovery period (Fig. 42b).

Despite some loss for the majority of businesses in urban areas due to direct damage or limited accessibility, there are marginal reports of some positive outcome during floods due to local residents unable to shop far away. In rural areas, an increase in fish caught in post-flood waters is also occasionally mentioned (Jarungrattanapong & Manasboonphempool, 2011).

The post flood recovery varies from a few hours to days or weeks in rural and poorer areas. Recovery signifies a return to usual conditions for the population that include access to drinking water, running water, electricity, food and labor (Tachaudomdach *et al.*, 2021).

Post-2005 flood surveys show that 75% of respondents wish they would pay more attention to weather updates but this percentage has probably significantly decreased with information availability. Among the rural population, 40% would consider harvesting earlier if the flood warning allowed it (Jarungrattanapong & Manasboonphempool, 2011).

A significant part of the population living in a single story house consider adding a level to their house or raise the ground to lower the risk of indoor flooding when it is possible. In many cases, financial constrains are the main limitation. Some flood victims also sought of getting a water damage insurance cover but 40 to 60% consider it is not worth it since there is little chance to get a cover for a high flood risk area, especially with the recent history of flooding (Jarungrattanapong & Manasboonphempool, 2011).

Most urban victims are not particularly interested in getting temporary work during floods if their normal occupation is not possible. However, rural residents are more interested in this idea (12%), probably due to flooding lasting sometimes several weeks in some farmlands. Around one quarter of the rural population also express that they would not change anything either because they are unable (physically or financially) or expect the government to find solutions for the next flood (Jarungrattanapong & Manasboonphempool, 2011).

Following the floods of 2005, one third of urban residents considered to relocate while only 4% are interested by this option in rural areas. While the new flood protection made prior to 2005 failed to protect the city, 23% of urban residents at the time thought that flood are going to be less severe in the future due to additional projects for the waterways while 28.5% thought that floods will be more severe (Jarungrattanapong & Manasboonphempool, 2011). No data is yet available for post-2024 floods but it is likely that this latter opinion has similar percentage or higher. Although some projects such as the Mae Kuang Udomthara Reservoir Project might alleviate some flooding, the public might not be sufficiently informed to have a meaningful opinion on the effect of this mega-project and is possibly skeptical of the other promises that were already made post-2005.

6.2.4. Politics

Political discourse following flood disasters is mostly seen as opportunities for politicians to be instrumental in making bureaucracy more responsive. The 2005 floods were followed by numerous political responses but with little real changes down the line (Garden, 2007; Lebel *et al.*, 2007). The same political rhetoric was seen in southern Thailand floods a few months later, in 2011, etc. In rural areas, politicians are also active to bring the drought narrative at the beginning of the dry season to capture rural electorates with the support of farmers, rural officials and the RID (Lebel *et al.*, 2009) but floods do not bring much consideration due to their relatively lower impact on income in rural areas, the fatalist approach towards it and the supposed assistance of disaster relief at higher governmental levels.

An unfortunate but recurrent political response to the cause of floods in urban and low lands area is also to impose the blame on mostly defenseless social groups such as uplands non-Thai due to their farming practices and the hypothetical role they would have in an equally hypothetical recent deforestation. This deeply ingrained Thai tradition to blame upland non-Thai and rural population is kept as it is since there is no concerting with such social groups (Becu *et al.*, 2003; Walker, 2003) and is regularly applied to floods, drought, burning season, environmental pollution, etc. The oversimplification of the issue to explain urban flooding is very uncertain but hill tribes makes convenient scapegoats rather than admitting that recent floods are in a large part, an urban development problem (Manuta *et al.*, 2006).

On the impact of drought, the increase of the GINI coefficient (inequality index) for water resources in the North progressed from 0.55 in 1989 to 0.69 in 2000 for potential resources and 0.62 (1989) to 0.72 (2000) for availability (Ekkawatpanit *et al.*, 2013). The urban-rural divide that has increased in the past two decades probably accentuated that inequality regarding water resources and is a clear indicator, if anything, that the rural population is increasingly marginalised in access and use of water resources and the impact they could have on the catchment as a whole.

The flooding issues in the Ping river as it passes through Chiang Mai is seen in all major rivers of Thailand and is more adequately explained by a lack of proper urban planning, a lack of effective administration and management, environmentally inadequate projects, improper land use, mismanagement of waste water, encroachment, decades of Bangkok-centric water policies, etc. than modifications of the catchment itself. While sub-district and even district level political pressure can only apply to organization and preparation of an incoming flood and assistance during and post-flood, significant adaptation to flood and implementation of changes for future events can only be done at higher administrative levels (provincial, federal, royal) (Jarunrattanapong & Manasboonphempool, 2011). As a result, the causes of recent floods are mostly left untouched by politicians as it would lead to direct confrontation with social groups and high-ranking administration representative able to efficiently defend themselves on their lack of action.

6.3. Water management, flood & drought mitigation

As it is often the case in Thailand, coordination between agencies (see table below) is difficult due to a top-down bureaucracy that limits any collaboration at a horizontal administrative level. Little concertation exists between water & irrigation management, disaster management, urban planning, etc. (Manuta *et al.*, 2006). Each institution also displays poor effectiveness due to poor design, absence of checks and balances, monitoring and evaluation, preventing appropriate responses, all characteristics seen in most Thai administrative bodies and described in the literature as institutional incapacities (Manuta *et al.*, 2006).

	Name	Organizational unit
RID	Royal Irrigation Department	Ministry of Agriculture & Cooperatives
HWMC	Hydrology and Water Management Center	Upper Northern Region
DDPM	Department of Disaster Prevention and Mitigation	Ministry of the Interior
RFD	Royal Forest Department	Ministry of Natural Resources & Environment
	Chiang Mai Province	Province
	Chiang Mai City Municipality	District
	Sub-District Administration Organization	Sub-District

Table: Key institutions in water management in Chiang Mai.

6.3.1. Infrastructure and river management

Common infrastructure solutions to flooding and droughts include river bed management through dredging, bank revetment, channelization and deepening, widening of rivers but also irrigation canals, dedicated flood plains and diversion tunnels, dams and weirs, reservoirs, etc.

Dredging is a commonly offered solution to flooding as it lowers the river bed to an historical level and increases the flow of water. To be effective, dredging would have to be an annual process and it is unlikely that a budget would be permanently allocated to it (Jarungrattanapong & Manasboonphempool, 2010). Some recent studies on the economic feasibility of such maintenance have indicated that while the price of river sediment in the lower Ping is pretty low (100 THB/m^3), it would rise to 300 THB/m^3 in Lampang, Lamphun and Mae Hong Son and reaches its highest price in Chiang Mai at 580 THB/m^3 (Rangsiwanichpong & Melesse, 2022). Such prices in the Upper Ping would indicate that the benefit/cost ratio of dredging the river sediments for construction and agricultural nutrients could be positive (Fig. 43).

The effectiveness of dredging is clearly demonstrated and logical as it provides more volume and less obstacles for water flow and increase the overall channel conductivity. The 2005 floods, despite a record flow volume for the Ping river, had a lower river stage than 2011 or 2024, in part due to the previous dredging of the Ping river. Politically, dredging as well as channel straightening, which is essentially dredging of banks with similar effects, is seen as an efficient way to give the psychological impression to the public that the government is doing something (Jarungrattanapong & Manasboonphempool, 2011). However, not everything about dredging is positive as it negatively impact the ecosystem by damaging habitats. It also mobilises very large quantity of sediments and contribute to channel instability. In the dry season, a fully dredged channel bring the water table to a significantly lower level that could impact irrigation for agriculture (Jompakdee, 2004) (Fig. 44).

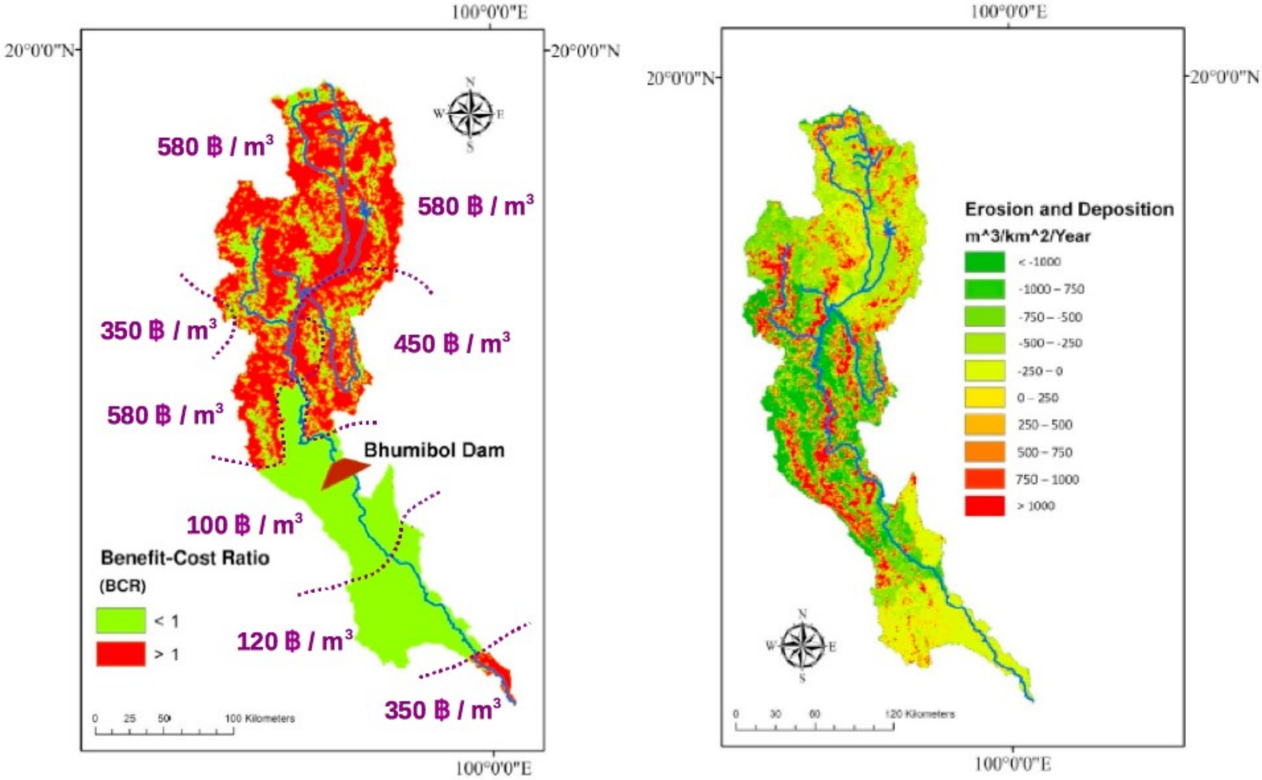


Figure 43. Right: Erosion and deposition rates in the Ping river catchment. Left: Approximate cost of fluvial sediments in the Ping river catchment broadly increases from Bhumibol dam to upstream sections. Areas in red are hypothetically zones were dredging is a directly profitable enterprise (modified from Rangsiwanichpong & Melesse, 2022).

Bank revetments made of concrete structure can prevent erosion and eventually flooding (as levees) and producing higher flow rate. However, such embankments makes the river narrower and make assumptions on the highest river stage that could be reached. In some places such as Sukhothai, the use of bank revetment has decreased the flood section to a point where higher water levels are reached for similar flow volumes (Jarungrattanapong & Manasboonphempool, 2011). Concrete revetments also degrade the Ping river landscape and the ecosystem by producing a canalized river of little environmental value (Jompakdee, 2004).

Encroachment, along with unsuitable embankments, is considered a significant cause of the 2005 floods. The long term project to bring the Ping river back to its 1969 size when it was wide and would flow through the city faster, allowing a flow volume equivalent to a current +4.2 m river stage causing no flooding was never achieved since attempts to control encroachment have been mostly unsuccessful or poorly enforced (Jarungrattanapong & Manasboonphempool, 2010; 2011). The city levee project that was started in 2004 and done for 6 kilometers of length in Chiang Mai, has increased locally the flooding level from +3.4 m to the current +3.7 m but it was clear before the project was even completed that it would exacerbate flooding elsewhere (Jarungrattanpong & Manasboonphempool, 2011). Recent studies suggest this levee project should be carried for another 16 kilometers to reduce the flood risk over the whole area rather than just transferring the issue downstream (Tansar *et al.*, 2021).

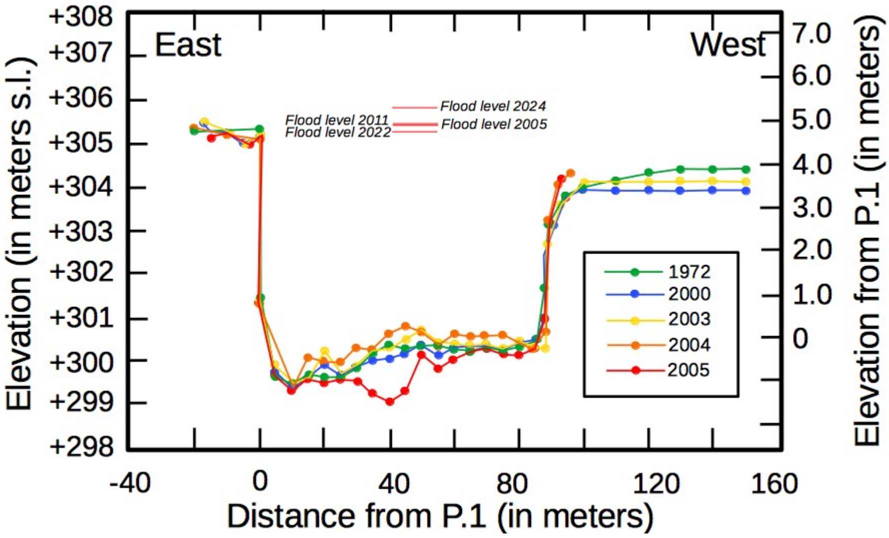


Figure 44. Transect profile of a dredged Ping river bed at P.1. in 1972 and between 2000 and 2005 (modified from Chaipimonplin, 2010)

Weirs have been traditionally present along rivers in Northern Thailand. In the past century, these have been modernised into concrete weirs and a large number of new ones were added since the 1980s (Fig. 37). Their main purpose is to reduce river flow and accumulate water upstream, to maintain a base level in the dry season and be used during droughts. However, weirs have a detrimental effect during floods, by causing significant obstacles to river flow and reducing the conductivity and inducing a lot of sedimentation on the river bed. These issues have been considered and a number of those weirs are now overhauled into small dams with suitable flood gates. Following the 2024 floods, there has been some discussion to remove several weirs on the Ping river that are falling in disrepair or redundant with more recent flood gates.

Dams and reservoirs are very efficient at managing river flow for both dry and rainy season taken separately. In the rainy season, runoff can be retained into reservoirs and released progressively later on while in the dry season, water is accumulated and released throughout the season to be available for water consumption. In practice however, the water management is made more complicated when considering maximising water storage for the beginning of the cold season while leaving enough volume to absorb the large rainfall events occurring at the end of the rainy season. As a result, in some particularly intense rainfall events, reservoirs can reach their capacity and lose their ability to minimize flood volumes. On the negative side, dams can have a significant impact on bed degradation downstream due to accentuated erosion and armouring of the riverbed upstream with coarser materials being cemented into a silty matrix (Jompakdee, 2004) and producing a generalised sediment clogging.

Finally, the RID has more active processes to manage water such as pumping flood water in some conditions or diverting water into other rivers and canals to reduce the flood impact in a specific area. Some of these canals are relatively long such as the channel along the ‘canal road’, west of Chiang Mai that brings water from the Mae Taeng weir, 60 kilometers downstream through Chiang Mai, into the Mae Khan, then Mae Wang and eventually into the Mae Ping in Pa Sang, Lamphun province (Fig. 45).

6.3.2. Repurposes and conflicts between stakeholders

The whole exercise of water management in Northern Thailand is to find the balance between preserving water for agriculture, irrigation and urban water supply by keeping sufficiently high water levels in the dry season but also low levels in reservoirs during the rainy season, eliminating the risk of flood in downstream rivers. Dry season water management is now benefiting of relatively good prediction of water usage for farmers growing in season crops with gross margins on requirements taken into account (Yotapakdee & Havrland, 2012). Rainy season management is a lot more complicated as water reservoirs are prepared to buffer large runoff during tropical storms but the lack of sufficiently effective medium term forecasting for such events leaves a lot of uncertainty on what should be done (Jarungrattanapong & Maansboonphempool, 2011).

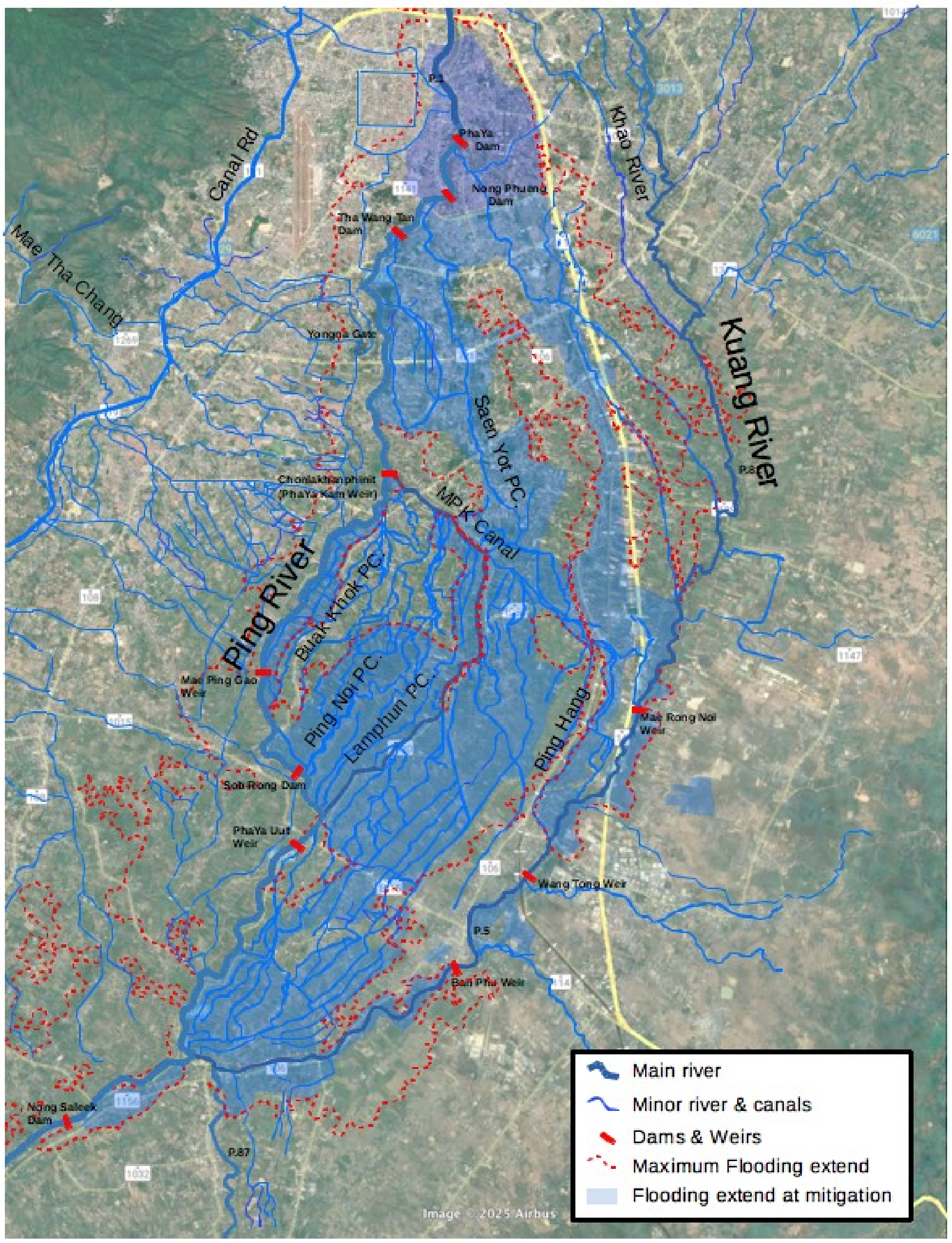


Figure. 45. Chiang Mai-Lamphun area during the 2024 floods (red dashed line) along with rivers and canals that covers the region and are used for drainage of flood waters (inspired from RID Action Plan 2024 and UNOSAT, 2024)

The irrigation programs started in the middle of the 20th century, replacing the traditional muang-fai weirs (in the North) by modern concrete dams with water gates. This new infrastructure financed by the state gave immense control to the RID which became the main authority and source of expert knowledge regarding water management and where individual, non-central governance and experts were reduced to an observing role. As such, this modernisation of the irrigation system allows the RID to impose upstream rules to most farmers with minimal notification, consultation or cooperation with local irrigation systems (Tan-Kim Yong *et al.*, 2005). It is therefore not surprising that the RID infrastructure is opposed by some rural groups as local communities lost power over local water management and see it as a state intrusion into what was a community managed system in the past (Lebel *et al.*, 2009; Jarungrattanapong & Manasboonphempool, 2011).

Initially, dams were built to manage water during drought and effectively, only replacing the muang-fai with a more efficient and resilient system. However, due to increasing urbanization, some large dams were quickly repurposed in producing electricity for the urban-industrial development in suitable areas and, as a corollary to this development, regulate monsoonal flows (Lebel *et al.*, 2009). While original projects were to provide agricultural water during drought, they now mean to provide water to urban and industrial users and manage flood risk to minimize damage in urbanized areas. Progressively, and similarly to the Bangkok-Central Plains attitude towards the Upper Ping, a clear urban bias has arisen in the Upper Ping management where agriculture lost priority for urban needs despite conflictual announcement by state representatives that water management and irrigation projects are for the benefit of agriculture (Lebel *et al.*, 2009).

Water management also cannot be separated from the catchment management and particularly land use. Forested areas are natural and critical part of water management that is protected by a broad coalition of NGOs, RFD, conservationists, ecologists. This group sometimes frown upon more infrastructural and anthropogenic water management through reservoirs and irrigation which are on the other hand, supported by the RID, rural people and non-urban politicians (Lebel *et al.*, 2009). As a key issue, water shortage is seen by the urban-conservationist group as low water supply due to deforestation, ending discussions with a persistent focus on forest protection and systematically putting aside the dramatic increase in demand, mostly urban, as the primary cause to possible water shortages (Walker, 2003). Consideration for the role of forested areas in water storage during the dry season is also not entirely supported by scientific evidence (Walker, 2003) and there is a possibility that forests have the opposite effect by limiting the amount of water infiltration during the dry season (Forsyth & Walker, 2008; Lebel *et al.*, 2009).

In the past two decades of flooding, forest cover has brought more attention and a shift in water management moving from blue water (surface flow in rivers and reservoirs) to green water (soil moisture, evapotranspiration) resources has occurred, leading to further steps in forest conservation and management of upland watersheds to moderate the runoff. Although the effect of forest on runoff during intense rainfall is clearly a potential cause of flooding; field data, modeling and historical information on deforestation rates and spatial distribution, flooding records and water behaviour in these situations provide some nuances to the role of forests in Northern Thailand. The post-2005 floods reflection period resulted in several infrastructural changes but also an increased focus on the catchment. Under the Royal Forest Department, the management of the watershed in lowland plains was used as a tool to control upland resources. The claim of widespread deforestation occurring in the uplands has been spread for decades and used to support all kind of policies (Vandergeest & Peluso, 1995; Forsyth, 1998; Walker, 2003; Leblond, 2010; Mostafanezhad & Evrard, 2021; Beaulieu *et al.*, 2023). The management and classification of the watershed and the associated control over it is closely related to other issues of community forestry, preventing direct management of forest resources by local communities (Walker, 2004; Pirard & Charoenpanwutikul, 2023). In some aspects, the RFD emulates the behaviour of the RID, with changing objectives from primary forest exploitation, to native tree replanting for commercial wood, to concerns about biodiversity and upper watershed management. All those changes while constantly dissing the practices of non-Thai ethnic groups such as rain fed agriculture, Swidden-rotational systems and general forest management by presenting those minorities as using inappropriate methods and norms, translating into usual vague threat to national security, biodiversity and water supply (Forsyth & Walker, 2008). Depending on the chosen source of information, some hilltribes will be seen as forest guardians with no development other than subsistence farming and sustainability while others will emphasize the lack of ‘thainess’ and describe them as forest destroyers seeking any opportunity for commercialization (Forsyth & Walker, 2008). The Karen ethnic group is particularly exemplary of this situation as they have developed a reputation among academics and activists to be conversationist, forest-friendly, non-commercially orientated hill-tribe (Walker, 2001) but the reality is that subsistence-oriented, low-input, low-impact cultivation has progressively died out starting in the mid-80s following the change that occurred a couple of decades earlier for low-land farmers who have become increasingly commercially oriented with higher requirement from irrigation (Walker, 2003). However, uplands mostly see small scale irrigation systems and the actual farmland is not always an increase as some places show a decrease but a change in the type of crops is observed. While dry season cropping pre 1980s was water conservative vegetables & cattle, it is now irrigated paddy area for soybean and maize (Walker, 2003).

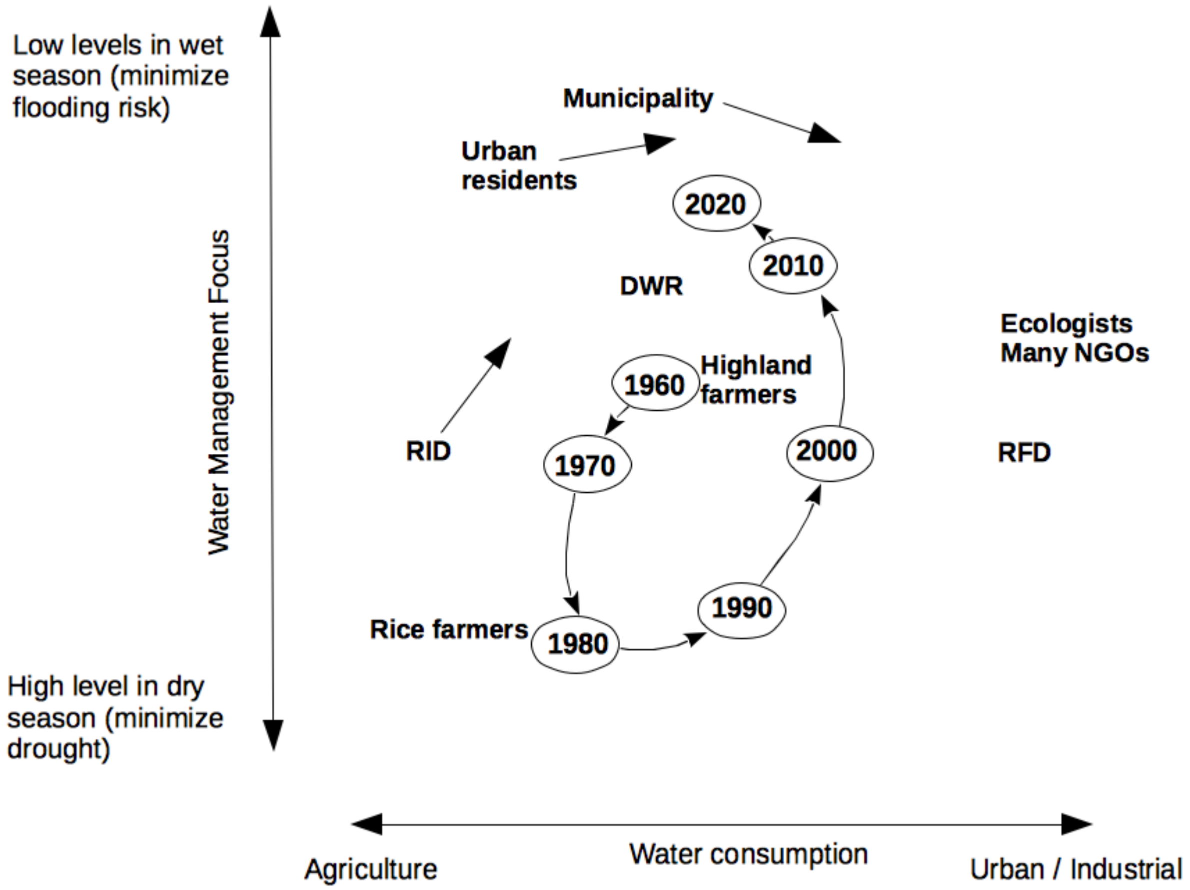


Figure 46. Schematic representation of the different stakeholders in water management. Dates show the approximate shift in water management policies between 1960 and 2020 (modified from Lebel *et al.*, 2009)

The HWMC is the main administrative body in pre-flood conditions that works through water level monitoring and produce early flood warning. After the 2005 floods, an increased public awareness and knowledge about flooding events appeared to be necessary for the public in the hope to have appropriate response towards flood risk and avoid some situations seen during 2005 such as places where dikes were built by the local population and undone in adjacent, similarly impacted zones. The main role of HWMC is forecasting and warning (Sriwongsitanon, 2010) and education remains a non-priority by any authority group, including the HWMC (Jarunrattanapong & Manasboonphempool, 2011); fortunately social media have organically filled that duty by propagating quickly and efficiently valuable information emanating from authorities.

The DDPM is mostly a syn- and post-flood acting organization that has policies on disaster management, prevention, maintenance, awareness & assistance and rehabilitation and coordination of assistance to victims. Policies are updated occasionally, sometimes in an attempt to be more pro-active during floods but since it is mostly a coordination agency, it has no substantial emergency budget of its own and any action during floods requires approval to assess funds and providing assistance to victims (Tingsanchali & Rewtrakulpaiboon, 2003; Jarungrattanapong & Mansboonphempool, 2011). Added to that, these policies and laws are rarely directly applied to cover flood mitigation, control, rehabilitation and recovery and are just vaguely related policies, laws and ordinances that often only remotely covers issues such as water management (Manuta *et al.*, 2006) and are subject to interpretation. Such administrative structure limits significantly its effectiveness and is possibly one of the reason why the army independently take action in some cases when imminent flooding is taking place (Fig. 42b). Reports from the 2005 floods show that even promises of post-flood relief, repairs and evident upgrades remained unfulfilled and can be delayed by several years (Manuta *et al.*, 2006). To some extent, it is still the case in 2024 where allocated budgets do not cover some of the flood damage and relief of public and private areas or in some cases, recovery support is conditional, unproductive and inefficient, purely due to administrative rigidity.

Finally, structural mitigation and repairs are rarely undertaken by local authorities due to the lack of funds and is under the jurisdiction of provincial, federal and royal levels. It includes modifications of water channels, bank protection and dikes (Sriwongsitanon, 2010; Promping *et al.*, 2019) and all flood damages to these structures. While the RID has a role to play in the management of headwaters (in collaboration with RFD), warning systems (in collaboration with HWMC), the structural base and main drainage of major roads (in collaboration with the ministry of transport) and minor roads and encroachment (in collaboration with local authorities), it ultimately falls under its jurisdiction to plan and deal with modification of water flow, dredging, retention ponds, reservoirs, diversion tunnels, new water gates, replacement and repairs of weirs, new river revetments and repairs and reducing/preventing river encroachment; slowing down considerably some recovery, repair and upgrading processes.

7. Long term trends and climate change modeling

7.1. Modeling

7.1.1 Generalities

Over the years, many models have been applied to the Ping river to explain its general behaviour (Schreider *et al.*, 2002; Taesombat & Sriwongsitanon, 2006; Vongtanaboon *et al.*, 2008; Mapiam & Sriwongsitanon, 2009) and flooding events (Tingsanchali & Gautam, 2000; Patsinghasanee, 2004; Patsinghasanee *et al.*, 2004; Sukka, 2005; Puttaraksa *et al.*, 2005; Thaisawasdi *et al.*, 2007; Ninprom & Chumchean, 2009; Chidthong *et al.*, 2009; Taesombat & Sriwongsitanon, 2010).

The initial input into modeling requires hydrological rainfall and runoff in the catchment with all variables (interception, infiltration, depression storage, evaporation) and an estimation of all hydraulic processes occurring in the river channel and flood plain (subsurface flow, groundwater flow, overland flow and channel flow) (Taesombat & Sriwongsitanon, 2010). Historical hydrological data (1952 for rain; 1921 for river flow gauges), flood surveys on depth and duration and remote sensing are particularly useful for model validation (Boonrawd & Jothityangkoon, 2015).

Initially, simulations were 1D hydraulic models using St Venant equation (Navier-Stokes equations in shallow-depth systems) where the concept was to have a series of cross-section where the main input is flood inflow, simulating flood magnitude and depth downstream. These 1D models were essentially a linear interpolation of flood characteristics in each cross-section used where non-linear storage (inflow) and discharge (outflow) are balanced with some additional parameters such as transition factors between in-bank and over-bank flow. To approach the real topography of a floodplain, up to 140 cross section between P.20 and P.73 of the Ping river and 35 cross sections of Mae Kuang were used for this type of modeling (Sriwongsitanon, 2010).

When computation capability started to allow it, 2D flood models used a series of finite elements and finite differences calculations with flood depth, spatial extent and velocity in each step (Tansar *et al.*, 2021). The studied system is rasterised initially to lighten up the computational requirements, but also to allow reverse modeling when inadequate input data (hydrological, structural, topographical) is present. In these rasterised models, the flood is divided into storage cells using a finite element approach of volumetric flow in each unit. In each cell, St Venant equations are used with several controlling parameters, with the exception of advection which is negligible in most flooding areas in Chiang Mai. While 1D model works on a flat water assumption in each cross-section, 2D and 3D flood plain inundation models can use a downhill flow in the main channel and outward flow in the floodplain, which is a lot closer to real hydrodynamic conditions (Boonrawd & Jothtyangkoon, 2015).

Progressing with the computational abilities, more and more data were added to the model, with detailed topographic maps and the additional input of light detection & ranging (LiDaR) and synthetic aperture radar (SAR), significant additional details such as in-bank and over-bank flow characteristics, buildings distribution and infrastructure details such as road surfaces, small canals and sub-surface drainage, etc. as well as the geometry of the main channel, its slope and very detailed cross-section of the floodplain are valuable information but becomes very quickly very complex and requires some rasterization for large-scale complex floodplains such as CML basin (Boonrawd & Jothtyangkoon, 2015).

The analysis of surface features with the heterogeneous effects of houses, buildings and other structures can be integrated in a model as flow resistance, similar to what was classically done for different type of vegetation covers through the Manning coefficient (Komsai *et al.*, 2016). Ground infiltration can also be integrated into a remote sensed map of flow velocity, all combined to give hydrodynamic modeling of the basin, using terrain data to simulate spatiotemporal variations of water behaviour, providing more accurate results than hydrological modeling, remote sensing, historical investigation and field surveys alone (Tansar *et al.*, 2021).

7.1.2. Flood forecasting

IHACRES is a non-linear module to transform rainfall data into effective rainfall (runoff) followed by FLDWAV, a hydrodynamic linear module computing antecedent streamflow with effective rainfall and producing a rainfall-flood model based on historical data. The model uses gauge stations in sub-catchments for validation by downstream river gauges (Sriwongsitanon & Taesombat, 2011).

Neural networks are another approach to modelisation using data with or without apparent physical relationships. With such approach, modeling of peak and post-peak flow between P.67 and P.1 is within 5% error for t+6 and t+12 hours which is seemingly a slightly lower error than projection used for public announcements (Chaipimonplin, 2016).

Neural networks are also used to model raw radar reflectivity values to produce hourly forecast values of runoff (Chidthong *et al.*, 2009; Chaipimonplin, 2010; Chaipimonplin *et al.*, 2011). Lumped models (homogeneous rainfall over a catchment) fail for large complex catchment such as the upper Ping. Some was alleviated using higher resolution hydrography network and rainfall records but it becomes increasingly complex to model such semi-distributed system (Mapiam & Sriwongsitanon, 2009; Mapiam *et al.*, 2014) and radar rainfall eventually becomes a better data source to quantify spatial distribution and intensity of hourly rainfall (Mapiam & Chautsuk, 2018) (Fig. 47).

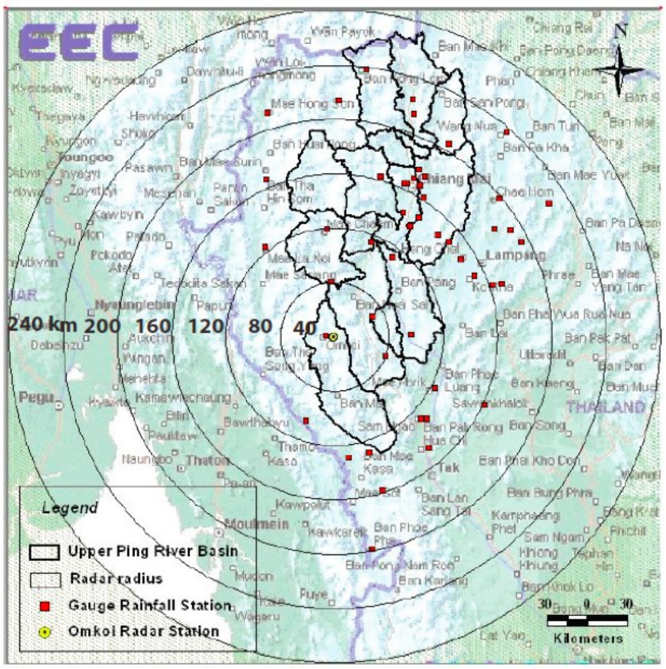


Figure 47. Map of the Upper Ping river catchment centralised on the Omkoi weather radar with its detection range (circles) and rainfall station (Mapiam & Sriwongsitanon, 2008).

7.1.3. Flood dynamics

2D or 3D models based on precipitation, interception, infiltration, runoff and flow routing provide situations that can be compared to the real flood and better identify the roles played by specific land features such as canals & drains, roads, buildings, etc. For example, the 2011 flood modeling show that a better fit with the real flood was obtained when the storage role of rice paddies in the floodplain was taken into account with the addition of a 20 cm high separation ridge between fields, changing the value of the Manning coefficient in the flood plain. The direction of the overflow is also significantly affected by the obstruction created by elevated roads such as the outer ring that stands 2 to 3 m above the floodplain (Komsai *et al.*, 2016). The role played by roads has also been explored in other models as enhanced conveyor zones of quick flow in a fragmented landscape. While roads have only a small effect on mean water fluxes, peak flows can be significantly increased, with an effect considerably higher than extreme deforestation cases (Cuo *et al.*, 2008).

Hydrodynamic modeling also show how natural factors can influence the flooding dynamics. For example, a model designed by Boonrawd & Jothityangkoon (2015) showed that an ideal case of a flat flood plain with a sudden rise of water in the main channel by 1 meter takes around 10 minutes to reach a distance of 3.6 km. The same conditions in a flood plain with a slope as little at 1 meter per kilometer requires 8.5 m of flood to reach such distance in a meaningful time.

Main channel hydrodynamics also show that just south of the Iron Bridge, overbank flow in 2014 was >510 m^3/s and for a volumetric flow of 530 m^3/s, the river stage would be 304.28 m.s.l. Models replicated observations where the right bank of the river would have flooding progressing 255 meters inland, the left bank would be spared of any flooding (1 m inland) due to river dynamics (Boonrawd & Jothityangkoon, 2015).

Modeling however reaches its limitation when non-natural variations are incorporated such as water release from the Mae Ngat reservoir or a loss of accuracy when a network of small streams or drainage system, sometimes unmapped and below the surface, can modify the water flow such as Mae Tha and the behaviour of Mae Kuang in Ban Thi and Lamphun area (Tansar *et al.*, 2021). In some cases, flood modeling can also overestimate the flooding potential of high rainfall such as events occurring early in the season when soil is undersaturated and runoff is minimal (Komsai *et al.*, 2016).

7.1.4. Other modeling

Some basic historical modeling has been applied to specific purposes such as the CENDRU (2013) warning and evacuation map which is abundantly shared by the media prior to a flood (Fig. 21). In the light of 2005 and 2011 floods, more specific models have been developed taking into accounts variables such as population density and number of households, water level, capacity and distribution of evacuation centres, type of aid packages available, cost & logistics for evacuation, storage capacity of relief depots, distribution of demand points, loading & unloading capacities, travel time, fleet size, transport modes, etc. All these factors can be compiled into a model that provide a response time for emergency services varying from 1 h (+3.7m flood) to 4 h (>4.6m flood). With 6-7 hours of warning between P.67 and P.1 and with the help of sufficiently accurate hydrodynamic models, the decision to evacuate an area or not, to establish relief supply centres and access routes, etc. can be taken hours before peak flow (Manopiniwes & Irohara, 2016, 2020).

At the opposite end of water management modeling is the drought forecast in the Ping river basin. Depending on the way its studied, three definitions can be found (Weesakul *et al.*, 2022). Meteorological drought is based on precipitation & temperature indicators (lack of rain, high temperature); Agricultural drought is based on remote sensing and vegetation conditions (various levels of hydric stress) and hydrological drought is given by indicators of streamflow, reservoirs and groundwater conditions (piezometric & baseflow levels; storage capacity). Droughts are generally assessed with various tools such as the Palmer Drought Severity Index (PDSI), the Standard Precipitation Index (SPI), the generalized Monsoon Index (GMI), etc. which takes into account the type of crops and their stage of growth in the studied area and their estimated sensitivity to drought. While historically, rice is not heavily affected by the lack of rain due to various natural & traditional parameters, lychees saw a 13% decrease in production in the 1998 drought (Ueangsawat & Jintrawet, 2013; 2014). With the help of numerous standardised precipitation indices (SPI, SPEI, PDSI, Smd, NDVI, VCI, SP, etc.) calibrated with the decile method (cumulative frequency distribution of rainfall into ten parts), modeling drought gives up to 78% of ground truth when calibrated to local conditions (Weesakul *et al.*, 2022).

7.2. Long term trends

7.2.1. Historical trends

Chiang Mai has around one hundred years of continuous weather and river records which provide some baseline to observe trends in the past century and how it would compare with climate change models for the next century.

Maximum temperature long-term average shows an increasing trend between the 1960s and 1980 followed by a decrease post-1980. This trend is partly due to high temperature records in the 70s and particularly 1979 which had 2.5ºC positive anomaly for maximum temperature (Reda *et al.*, 2012, 2013). Extreme maximum temperatures which fluctuate a lot between +38 and +44ºC tend to have high records (43-44ºC) in the past couple of decades (Reda *et al.*, 2012).

Minimum temperature shows a below average increasing trend until the 1980s and above average increasing trend post-1980, indicating that cold seasons are getting warmer. The trend is mild since the 1960 until 2010 when it increased by 1ºC (Reda *et al.*, 2012, 2013). The coldest mean temperature was 1971 with 3.7ºC below the normal minimum temperatures while the extreme minimum temperature was recorded in December 1999 with 3.8ºC for Chiang Mai.

Rainfall interannual variability is up to 450 mm above the long term average and 300 mm below (Reda *et al.*, 2012) which makes the identification of a clear trend more difficult. 1970 and 1988 have been identified has the wettest year while 1993 is the driest. Relative humidity is very stable with high records noticed for 1966 and 1977 (Reda *et al.*, 2012). Trends for rainy days show that 1-day rainfall and the number of rainy days per year has increased significantly since 1921 but not a 7-day rainfall which remained the same. The wet monsoon length itself is highly variable, with fluctuations above any discernible trend (Lim *et al.*, 2012) (Fig. 48).

Rivers show no significant increase in peak flow since 1921 indicating that on average, flood volume has not changed in the past century. However, the variability of all flow parameters has significantly increased along with a very significant decrease in minimum flows, annual and rainy season discharges (Lim *et al.*, 2012). The clear decline in minimum flow appears in the mid-1950s and is due to anthropogenic changes and human activities. The increased variability is visible as the 15 years running mean follow the long term mean until around 1965. Huge variations in the 1970s are observed until 1984 when flows stayed below mean value with the exception of peak flow. The last 50 to 60 years of high variability in river flow with no obvious trend is strongly correlated with significant anthropogenic activities (Lim *et al.*, 2012) (Fig. 49).

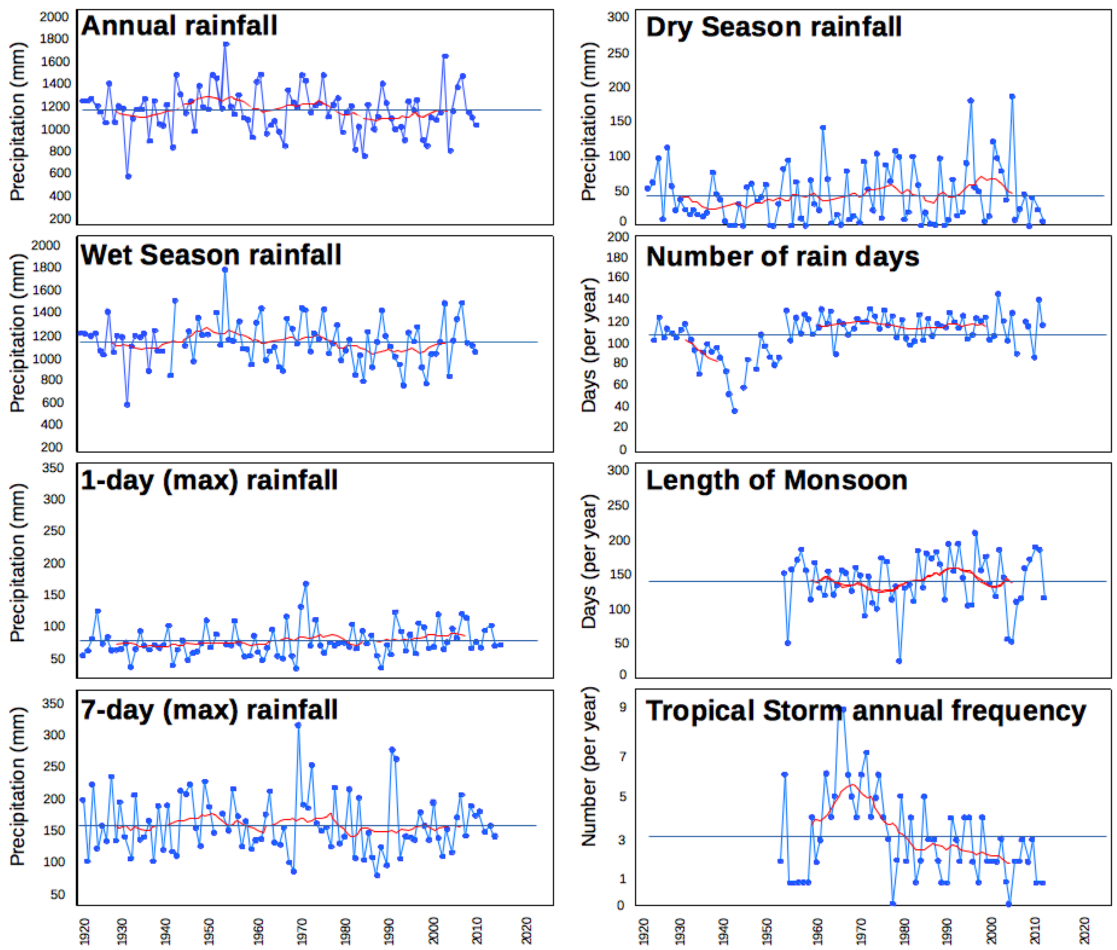


Figure 48. Long term variation in various meteorological parameters and 15-year average trends (red) between 1921 and 2012 (modified from Lim *et al.*, 2012).

River flow, like rainfall, does not show obvious trends and 66% of peak flow positive anomalies are associated with tropical storms, monsoon anomalies or ENSO with the top 3 peak flow linked with a strong tropical storm anomaly. The corollary is however not systematic, particularly for early tropical storms that have low to no effect on peak flow (1952, 1982) even if this early storm contributes for 10% of annual rainfall (Lim *et al.*, 2012). In the early 1990s, a low peak flow is observed and possibly linked to the 1991 Pinatubo eruption reducing rainfall (Trenberth, 2011) (Fig. 49).

Post-1980s, a strong correlation emerged between ENSO, temperature and rainfall, with warmer and dryer conditions during El Niño and the opposite during La Niña (Singharattana *et al.*, 2005; Reda *et al.*, 2012). The effect is only significant on rainfall and annual & seasonal streamflow for strong El Niño (resp. -36.3 & -44.7%) and La Niña (resp. +36.1 & +41.7%), reaching +35% above average rainfall during 2011 La Niña and -14.5% below average in 1998 during the North-East Thailand drought (Ueangsawat & Jintrawet, 2013). Association with floods and drought is not systematic as 1988, 1999 and 2007 are strong La Niña with no peak flow anomaly while El Niño 1987 and 2006 have higher flow than average (Lim *et al.*, 2012).

A tentative claim has been made that rainfall in South East Asia follows a 30-year cycle not forced by ENSO. According to this hypothesis, above normal rainfall occurred in 1880-1895 and 1930-1963 while 1895-1930 and 1963-1990 are below average (Kripalani & Kulkarni, 1997). A reappraisal of this hypothesis suggested epochs of 15 to 30 years, possibly linked to ENSO long term cycles exist with a 1935-1957 period of high base flow with a La Niña : El Niño ratio of 6:2 and 1966-1980 with a ratio of 7:4 while three drier epochs are known before 1935, 1958-1965 and 1991-2009 with respective La Niña : El Niño ratios of 2:3, 1:3 and 4:8 (Lim *et al.*, 2012). When El Niño is in phase with the low rainfall part of this hypothetical 30-year cycle, drought would occur (1923, 1932) while high rainfall combined with La Niña would produce significant floods (1938, 1970) (Kripalani & Kulkarni, 1997).

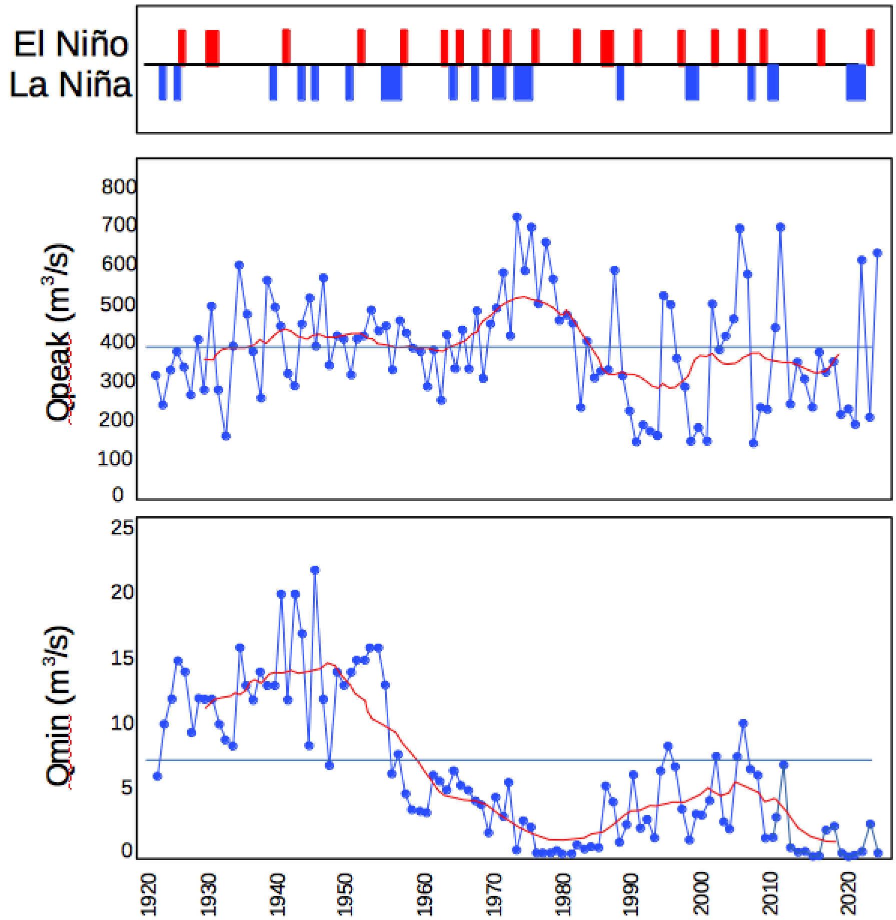


Figure 49. Long term variation in peak flow and minimum flow during the dry season and a comparison with the ENSO status (modified from)

7.2.2. Climate change models

Climate change is often invoked in the media, but also in official and research papers for all kinds of recent extreme events. In Chiang Mai, putting the blame on climate change is occasionally done for the burning season (Pirard & Charoenpanwutikul, 2023) and more frequently as the cause of flooding (van Dijk *et al.*, 2009; Sriwongsitanon, 2010; Bidorn *et al.*, 2016; Tikul, 2018) particularly in a narrative rhetoric that things are worse now than in the past. This is often done without reference or support for such idea other than broad global statements (IPCC, 2007). Although some academics use modeling to support their claim, it is often poorly designed and inappropriate models that have little relationship with reality and it is not surprising that most credible advocates of climate change are very careful not to draw simplistic and direct links between extreme events and climate change (Huntington, 2010).

The Global Climate Model (GCM) for South-East Asia gives +1.0 to +4.5ºC and -20 to +20% of precipitation resulting in -10 to +30% runoff for a grid size of 300*300 km^2, which is basically equivalent to the whole Northern Thailand (IPCC, 2001; Sharma *et al.*, 2007). GCM CMIP6 shows that in the near future, T_{max} will increase by 0.3 to 0.4ºC, T_{min} by 0.5 to 0.6ºC and rainfall increases of 8.1 to 11.2%. Mid-future projections give T_{max} increases of 1.2 to 1.9ºC, T_{min} of 1.3 to 2.0ºC while rainfall increase of 11 to 13.1% and for far future projection (>>2050), T_{max} increases of 1.9 to 3.9ºC, resulting in 37.17 to 39.38ºC from the 33.1ºC baseline. T_{min} is 2.0 to 3.9ºC above resulting in 25.5 to 28.6ºC compared to the 21.8ºC baseline. Rainfall would increase by 16.2 to 24% with individual models reaching highs of 2386 to 2543 mm/year mostly increasing during the rainy season. This is in turn lead to a projection of streamflow increase from 11 to 15.1% in the near future to 23.4 to 31.6% in the far future (Chapagain *et al.*, 2025).

However, this General Circulation Model is a global model to project the impact of climate change (precipitations, frequency & intensity, probabilities of droughts, seasonal streamflow, etc.) on a global scale, which is only acceptable for projections at continental and regional scales but requires other approaches for smaller geographical areas (Boonrawd & Jothiyangkoon, 2015). The statement that the magnitude and frequency of floods or that air pollution would increase in the near future as a consequence of climate and human induced changes (IPCC, 2007) is often presented, especially by the media, as an immovable statement while the IPCC report itself clearly states that extreme events such as flooding or wildfires have causes that cannot be predicted by a general circulation model.

While the GCM model can give extreme results with 1000% changes in some areas, an initial bias correction can be applied and such a bias-corrected GCM gives very significantly milder variations for these projections for the next decades (Sharma *et al.*, 2007). However, with the exception of the media, academics and officials in search of publicity and the use of inaccurate data in published papers; most studies on future local climate use statistical downscaling for their projection, which broadly consists of using global climate variables and local variations and assume that the statistical relationship between the two won't change in the future (Cheevaprasert *et al.*, 2020). Such assumption is certainly incorrect, but it's infinitely better than assuming a world following a homogeneous climate trend globally.

Downscaled models for the Upper Ping catchment provide a lot more nuanced, less dramatic and variable results than the GCM. Through the downscaling approach to project the local climate in a changing global climate, the effect on local meteorology and how local climate shifts (i.e. slightly more annual rain, slightly longer wet season, slightly drier dry season, etc.) can be translated into extreme events with associated uncertainties (Cheevaprasert *et al.*, 2020).

In this document, in order to homogenize information from the literature, the emission scenarios prior to the 5th assessment report of the IPCC (IPCC, 2014) have been reassigned to their closest representative concentration pathways (RCP). As such, B1 (global environmental sustainability) emission scenario is equivalent to RCP+4.5; A2 (regional economic development) is equivalent to RCP+8.5 (IPCC, 2007). Scenario A1 which was thought for a global economy-focused growth is towards or worse than RCP+8.5 while scenario B2 of slow growth with a focus on environmental solutions and local adaptation has no direct equivalent to RCP pathways and is likely an utopian future. RCPs are scenarios where the radiative forcing would reach +2.6, +4.5 or +8.5 W/m^2 in 2100 (IPCC, 2014). RCP+2.6 requires a drastic, immediate change in our effect on the global climate while RCP+8.5 is the 'business as usual' scenario of unhindered economic growth.

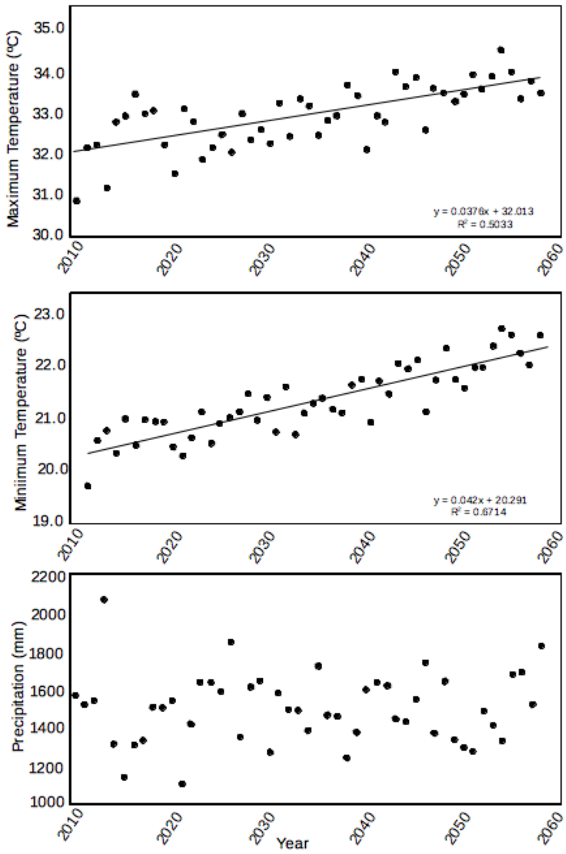


Figure 50. Example of climate change trends in the Upper Ping catchment between 2010 and 2060 for temperatures and precipitation using the ECHAM4 model (Reda *et al.*, 2013)

All scenarios, based on various models, give a significant rise of mean annual temperature of around 3ºC between 2000 and 2100 (Sharma *et al.*, 2007; Reda *et al.*, 2014) with an increase of 0.038ºC/yr for T_{max} and 0.042ºC/yr for T_{min} between 2011 and 2059 resulting in a possible longer hot season and shorter cold season. The increase is not linear and would be around 0.041 ºC/yr between 2015 and 2044, and 0.033ºC/yr between 2045 and 2075 (Ueangsawat & Jintrawet, 2014). By 2070, the increase of T_{max} in a RCP+8.5 scenario for Mae Rim is 1.07, 1.35 and 2.00ºC for cold, hot and rainy seasons (Ueangsawat & Jintrawet, 2014).

For precipitations, Saengsawang *et al.* (2017) show that most changes are stabilised by 2050 in an RCP+2.6 scenario with a reduction of rainfall in the wet season and the dry season, respectively by 6.3 and 12%, resulting in a reduction of rainy days in the wet and dry seasons by 4.3 and 15% respectively. In a RCP+4.5 scenario, rainfall would keep decreasing from 3.8% to 8.6% in the wet season and 10.3 to 16.6% in the dry season and similar values for wet days with 4.0 to 5.1% in the wet season and 13.3 to 18.5% in the dry season by 2100. Finally, in the RCP+8.5 scenario, rainfall would decrease by 4.2% to 12.6% in the wet season and 11.6 to 27.2% in the dry season and similar values for wet days with 4.4 to 7.8% in the wet season and 15.6 to 25.8% in the dry season by 2100 (Saengsawang *et al.*, 2017) (Fig. 50).

Other models provide opposite results with an increase of up to 20% in rainfall (Reda *et al.*, 2013; Wuthiwongyothin *et al.*, 2019) or even 50% increase in the 2006-2025 period (Norse, 2003). Models using increasing radiative forcing up to RCP+8.5 have an increase in rainfall from 31 to 104% (Boorawd & Jothiyangkoon, 2018).

Finally, some models are more indeterminate and show a slight increase in the northern provinces while the central plains have a decrease of rainfall (Saengsawang *et al.*, 2017) or minimal changes during the rainy season and slight increase in cold and dry season (Ueangsawat & Jintrawet, 2014) or no significant trend for rainfall and relative humidity (Reda *et al.*, 2014) (Fig. 50, 51).

Models that predict up to 50% less rainfall are generally associated with a lower variability in rainfall anomalies (Sharma *et al.*, 2007) making extreme rainfall events even rarer while on the other hand minor increase in rainfall for a same seasonal length would technically bring higher rainfall intensity with significant errors (Reda *et al.*, 2013).

The wrong prediction of Norse (2003) for the past couple of decades with 50% additional rainfall hypothesized that it would increase the frequency and intensity of extreme events. While flooding events in Chiang Mai seem to support that idea, the volume of water and the rainfall causing those floods were not abnormal. Finally, minor changes in rainfall between the rainy, cold and dry season, especially in scenario where it reduces the contrast between those seasons, would bring significant changes in water use and management for agriculture (Ueangsawat & Jintrawet, 2014). For example, for the period 2015-2074, the drought risk appears to decrease, but not directly making drought less common but rather increase the occurrence of wet events which could reduce the risk (Ueangsawat & Jintrawet, 2014).

7.2.3. Future trends for the Ping river

Based on climate change models, streamflow of the Upper Ping is expected to decrease by 13 to 19% of annual streamflow with a shift of seasonal streamflow later in the season from Aug-Sep to Oct-Nov as well as a significant increase in April producing more flow in the dry season (Sharma & Babel, 2013). Other models give a Ping runoff that would increase of 13.7% for RCP+4.5 and +8.5 while a GCM gives 17.3% increase by 2100 (Wuthiwongyothin *et al.*, 2017) which show that modeling of the occurrence and recurrence of future floods in Chiang Mai remains very uncertain.

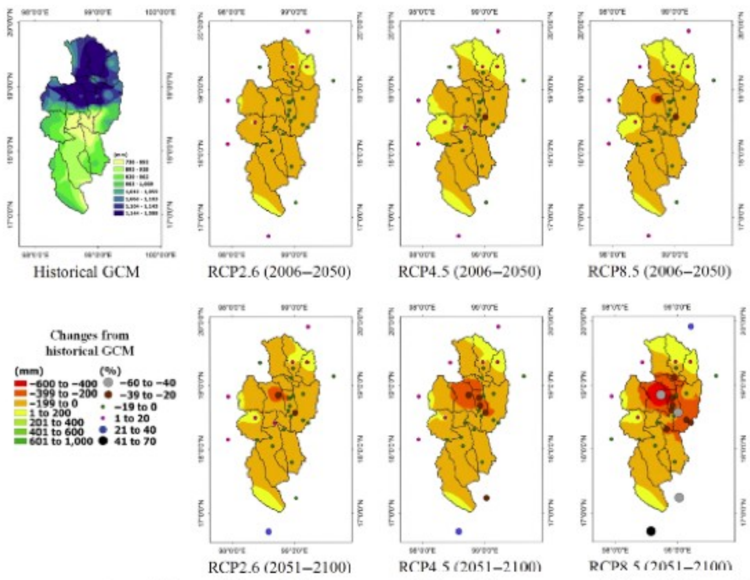


Figure 51. Another example of downscaled climate model for the Upper Ping basin (Saengsawang *et al.*, 2017)

The current data based on the 1954-2005 period has an annual flood peak flow between 370 to 450 m^3/s; a 10-year recurrence at 620 m^3/s and a 30-year recurrence at 750 to 850 m^3/s with 1952 or 2005 possibly the largest recorded floods over that period. Before 1950, the quantitative flood history of the Ping is less known but there is no doubt that floods such as 1525 or 1831 reached extreme flow volumes. In terms of flooded surfaces, 600 km^2 is the average biennial flood; 800 km^2 for 10-year return rate, 880 km^2 for 25 years, 935 km^2 for 50 year and 1000 km^2 for 100 year return rate (Tansar *et al.*, 2021). Some climate change models provide an expected increase of 89.5% for 10-year return, 91.2% for 25 years return, 20.8 to 30.4% for 50 years return and 10.2 to 22.1% for 100 years return (Boonrawd & Juthiyangkoon, 2018).

The extreme flood recorded in Mae Chaem in the early XXth century at a calculated flow volume of 2420 m^3/s (Kidson et al., 2005) is very significantly larger than the highest recorded historical flow in that catchment with 1030 m^3/s in 1960 (see 5.3). The authors of that study have suggested that the log normal distribution of flood frequency might not apply for extreme flood. The recurrence rate is generally established, among many parameters, through the Manning coefficient (surface roughness applied to water flow) and such coefficient is known to increase with high volumetric flow until it reaches a maximum and then potentially decrease (Kidson *et al.*, 2005). Kidson *et al.* (2006), supported by the study of other river systems, suggest that a power-law might be applicable for extreme floods and that 2500 m^3/s event could have a recurrence as low as 100 year while the standard model gives 84 years recurrence for 1000 m^3/s. In such model for the Mae Chaem river, the transition from log-normal to power law would occur at around 10 years (Kidson *et al.*, 2006).

This consideration brings some doubt that the official flood return model in Thailand, Gumbel EV1, a log normal distribution, might be accurate for extreme events. Since the Mae Chaem and uppermost Mae Ping are relatively similar in annual peak flow and geographical proximity, with the uppermost Ping being a catchment twice larger than Mae Chaem, divided in 3 main tributaries, it is questionable if the Gumbel EV1 is applicable for the Ping river passing through Chiang Mai for extreme events. Assuming that a similar extreme rainfall event occur on one the uppermost Ping subcatchment, 1200 m^3/s could be expected to be added to a Ping river with an already high monsoonal base flow, potentially producing a volumetric flow of 1500 m^3/s in P.1 (Fig. 52). Such volume would be twice larger than the largest 2005 flood. However, due to the basin shaped flood plain in the Chiang Mai area, the river stage would reach values similar or slightly higher than the 2024 floods assuming the main channel is dredged and in a similar conditions than during the 2005 floods. The flooded surface might reach a 1000 km^2 for the whole CML basin, representing one third of the whole surface while the most extreme historical floods only affected 10% of the basin. To our knowledge, other than dubious “simulations” on extreme floods, no study has been made on the effect of such floods in the basin and if these are at all possible in the first place.

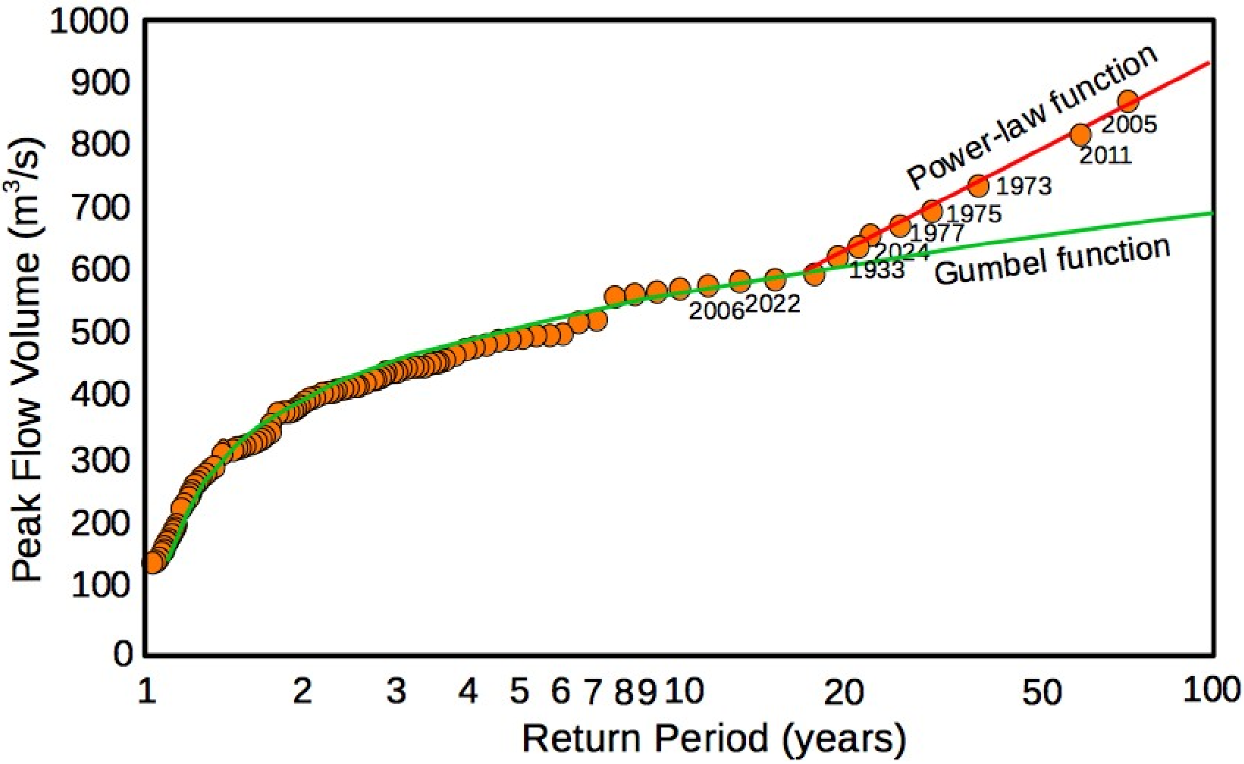


Figure 52. Graphic representation of return rate of floods in Chiang Mai based on the Gumbel EV1 function used by the government (green curve) and a power-law function (red) for events with a return rate higher than 20 years.

Finally, other water management models also focused on the modification of land use in the Chiang Mai – Lamphun basin and Upper Ping catchment. Since the 1960s, deforestation in the uplands but more importantly in the basin, has been extensive, reducing an original near-100% forest cover in the upper Ping river catchment to 72% in 2006 (Sriwongsitanon & Taesombat, 2011) which has arguable effects on water management, droughts and floods.

Chiang Mai itself had delayed growth until the 1970s due to the strong primate city role of Bangkok (McGrath *et al.*, 2017). In the 1980s, projects of the RID started to disrupt traditional village water management, partly decreasing peak flow variability (Ganjanapan, 1984). In the 1990s, the Ministry of Transportation and Department of Rural Roads started to upgrade and extend the road network for future urbanization with numerous highways, peaking by the end of the decade with the full development of the ring road system. It initially started with the development of the old tourist bus roads leading to places like Bo Sang or Ban Tawai, to then connect new commercial centers through a system of radial roads and additional rings or cross-cutting major roads to promote the development of mass market gated communities. This road system has triggered urbanization along them, through agricultural land and existing villages, modifying significantly the original gravity-fed irrigation system and leaving rice paddies inside these superblocks created by these roads as the last remnant of the traditional water management (McGrath *et al.*, 2017). As these superblocks are increasingly developed and urbanised, and in the absence of strict and enforced laws on water management, less flood basins are available and higher flood could be expected in the future for similar flow volumes.

In most projections of land use, agriculture which represents 27% of the complete Ping basin at the present time, is expected to increase to 35-43% (business-as-usual) to 57% (agricultural model) and only decrease in a full urbanization model. Forested areas, representing 65% at the current time, decreases in all scenarios down to 51 (full urbanization) to 37% (full agriculture). Urban areas represent 4% and would increase to 8% in a business-as-usual model; full urbanization could occupy as much as 30% of the basin in 2100 as an extreme scenario where Chiang Mai would becomes a large megacity (Chapagain *et al.*, 2025).

Modeling for water management and the future of agriculture is difficult as many changes might occur such as a shift from paddy rice to bioenergy (corn) and high value crops (orchards, flowers, spices) in the Upper Ping. Agricultural modifications caused by climate change can also have a significant impact. However, for rice, it has been shown that the average rice yield that increased from 2.5 to 2.8 t/ha between 1980 and 2000 and is now almost stabilised at 3.3 t/ha will eventually be projected to reach 4.2 t/ha by 2060 due to the correlation between yield, minimum temperature, relative humidity and rainfall (Reda *et al.*, 2014) with a linear impact on water management. However, the increase of minimum temperature, higher than maximum temperature for the period 2045-2075 at night time is expected to have some effect on growth response and carbon sequesttration (Peng *et al.*, 2013) and reduce photosynthetic activity through enhanced evaotranspiration and reduced soil water content (Ueangsawat & Jintrawet, 2014).

8. References

Alford, D. (1992). Streamflow and Sediment Transport from Mountain Watersheds of the Chao Phraya Basin, Northern Thailand: A Reconnaissance Study. *Mountain Research and Development*, 12(3), 257-268.
Becu, N., Perez, P., Walke, A., Barreteau, O. & Le Page, C. (2003). Agent Based Simulation of a Small Catchment Water Management in Northern Thailand: Description of the CATCHSCAPE Model. *Ecological Modelling*, 170(2-3), 319-331.
Beaulieu, A., Lebloond, J.-P., Dery, S. & Cao, H. (2023). Urban Air Pollution Anxieties, Forest Conservation, and Farmland Expropriation: State Territorialization in the Uplands and Highlands of Northern Thailand. *Land Use Policy*, 131, 106687.
Bhongaraya, S., Thiramongkol, N. & Choowong, M. (2009). Geomorphology and Formation of Gravel Beds along the Ping and the Wang Rivers at Tak, Northern Thailand. *BEST 2009*, 2(1-2), 11-19.
Bidorn, B., Chanyotha, S., Kish, S. A., Donghue, J. F., Bidorn, K. & Mama, R. (2015). The Effects of Thailand's Great Flood of 2011 on River Sediment Discharge in the Upper Chao Phraya River Basin, Thailand. *International Journal of Sediment Research*, 30(4), 328-337.
Bidorn, B., Kish, S.A., Donoghue, J.F., Bidorn, K. & Mama, R. (2016). Sediment Transport Characteristic of the Ping River Basin, Thailand. *Procedia Engineering*, 154, 557-564.
Boochabun, K., Tych, W., Chappell, N.A., Carling, P.A., Lorsirirat, K. & Pa-Obsaeng, S. (2004). Statistical Modelling of Rainfall and River Flow in Thailand. *Journal of the Geological Society of India*, 64, 503-515.
Boomgaard, P. (2006). Southeast Asia: An Environmental History, *ABC-CLIO*, Santa Barbara.
Boonchum, T., Taesombat, W. & Chompuchan, C. (2020). Evaluation of Satellite Monthly Rainfall Product PERSIANN-CCS using Rain Gauge Stations over the Upper Ping River Basin. *Thaksin University Journal*, 23(3), 41-50.
Boonrawd, K. & Jothityangkoon, C. (2015). Mapping Temporal Extent of Chiang Mai Floods using Coupled 1-D and quasi 2-D Floodplain Inundation Models. *Songkhanakarin Journal of Science and Technology*, 37(2), 171-181.
Boonrawd, K. & Jothityangkoon, C. (2018). Assessing the Climate Change Impact on Floodplain Inundation Map in the Chiang Mai Municipality, Upper Ping River Basin of Thailand. *Lowland Technology International*, 20(2), 213-220.
Bradshaw, C.J.A., Sothi, N.S., Peh, K.S.J. & Brook, B.W. (2007). Global Evidence that Deforestation Amplifies Flood Risk and Severity in the Developing World. *Global Change Biology*, 13, 2379-2395.
Bruijnzeel, L.A. (2004). Hydrological Functions of Tropical Forests: Not Seeing the Soil for the Trees? *Agricultural Ecosystem & Environment*, 104, 185-228.
Buapeng, S., Sanghabun, S. & Lauphensri, O. (1995). Environmental Isotope Study of Groundwater in Chiang Mai Basin, Northern Thailand. *Department of Mineral Research Annual Technical Meeting*, 11-13/01/1995, Bangkok.
CENDRU – Civil Engineering Department Chiang Mai University Natural Disaster Research Unit (2013). Flood Risk Map based on river stages for floods of 1994, 1995 and 2005.
Chaimanee, N. (1997). Some Characteristics of Quaternary Sediments in the Chiang Mai Basin. *In:* Thai-German Technical Cooperation Project Environmental Geology for Regional Planning. *Technical Report*, 19(6), Bangkok & Hannover.
Chaipimonplin, T. (2010). An Exploration of Neural Network Modelling Options for the Upper River Ping, Thailand. *PhD Thesis*, University of Leads, 273p.

Chaipimonplin, T., See, L. & Kneale, P. (2011). Improving Neural Network for Flood Forecasting using Radar Data on the Upper Ping River. *19th International Congress on Modelling and Simulation, Perth, Australia, 12-16/12/2011*. 1070-1076.
Chaipimonplin, T. (2016). Investigation Internal Parameters of Neural Network Model for Flood Forecasting at Upper River Ping, Chiang Mai. *KSCE Journal of Civil Engineering*, 20(1), 478-484.
Chaito, T., Khamkong, M. & Murnta, P. (2019). Appropriate Transformation Techniques to Determine a Modified Standardized Precipitation Index for the Ping River in Northern Thailand. *EnvironmentAsia*, 12(3), 32-42.
Chaito, T., Nakharutai, N. & Khamkong, M. (2021). Application of the Length-Biased Weibull-Rayleigh Distribution to Fit the Rainy Season Rainfall for the Upper Ping River in Northern Thailand. *Applied Mathematics and Computational Intelligence*, 10(1), 288-300.
Chaiwongsaen, N. (2018). Influences of Geologic Conditions and Anthropogenic Activities on Changes of Geomorphology and Sediment Load Characteristics of the Ping and Chao Phraya Rivers. *Chulalongkorn University Theses and* Dissertations, PhD Thesis 2390.
Chaiwongsaen, N., Nimnate, P. & Choowong, M. (2019). Morphological Changes of the Lower Ping and Chao Phraya Rivers, North and Central Thailand: Flood and Coastal Equilibrium Analyses. *Open Geosciences*, 11, 151-171.
Chaiwongsaen, N. (*n.d.*). A Proposed Conceptual Model for Effects of River Regulations: A Guideline for the Study of the Ping and Chao Phraya Rivers' Geomorphology.
Chapagain, K., Babel, M.S., Mohanasundaram, S., Shrestha, S., Luong, H.T. & Karthe, D. (2025). Impact Assessment of Climate and Land Use Change on the Water-Energy-Food Nexus: An Application to the Ping River Basin, Thailand. *Science of the Total Environment*, 25, 971, 179067.
Charuppat, T. (1998). Forest Situation in Thailand in the Past 37 Years (1961-1998). *Forest Research Office (Bangkok), Royal Forest Department.*
Chatchawan, S. (2005). Flood Situation and Flood Protection Report in Chiang Mai Municipal Area 2005. *Proceedings of the Academic Conferences: Towards Society Harmony, Thai Development Research Institute Foundation*, Chon Buri, Thailand, 26-27/11/2005.
Chidthong, Y., Tanaka, H. & Supharatid, S. (2009). Developing a Hybrid Multi-Model for Peak Flood for Forecasting. *Hydrological Processes*, 23, 1725-1738.
Cheevaprasert, S., Mehrotra, R., Thianpopirug, S.& Sriwongsitanon, N. (2020). An Evaluation of Statistical Donwscaling Techniques for Simulating Daily Rainfall Occurences in the Upper Ping River Basin. *Hydrology*, 7, 63, 7030063.
Chuamthisong, C. (1971). Geology and Groundwater of Chiang Mai Basin, Thailand. *M.Sc.* University of Alabama, USA.
Cuo, L., Giambelluca, T.W., Ziegler, A.D. & Nullet, M. A. (2008). The Roles of Roads and Agricultural Land Use in Altering Hydrological Processes in Nam Mae Rim Watershed, Northern Thailand. *Hydrological Processes*, 22, 4339-4354.
Ekkawatpanit, C., Kazama, S., Sawamoto, M. & Sarukkalige, P. R. (2013). Evaluation of the Inequality of Water Resources. *Water Management*, 166, WM6, 303-314.
Forsyth, T. (1998). Mountain Myths Revisited: Integrating Natural and Social Environmental Science. *Mountain Research and Development*, 18, 126-139.
Forsyth, T. & Walker, A. (2008). Forest Guardians, Forest Destroyers: The Politics of Environmental Knowledge in Northern Thailand. *Seattl: University of Washington Press - Book Reviews*, 481-482
Gale, E.L. & Saunders, M.A. (2013). The 2011 Thailand Flood: Climate Causes and Return Periods. *Weather*, 68, 233-237.
Ganjanapan, A. (1984). The Partial Commercialization of Rice Production in Northern Thailand (1900-1981). *New York, Cornell University*.

Garden, P. (2007). The Chiang Mai Floods of 2005. *Unit for Social and Environmental Research, Chiang Mai University, Chiang Mai*, USER Working Paper WP-2007-19.
Hinz, E.A., Liberty, L.M., Wood, S.H., Singharajawarapan, F., Udphuay, S. & Shragge, J. (2010). Student-based Archaeological Geophysics in Northern Thailand. *SEG Denver 2010 Annual Meeting*, 5p.
Hui Yian Lee, T., Ziegler, A.D., Marques dos Santos, M., Srinuansom, K., Tan, S.Y. & Snyder, S.A. (2024). Spatial and Temporal Patterns of Emerging and Persistent Contaminants in a Mixed-Use Catchment: A Case Study of the Upper Ping in Northern Thailand. *ACS EST Water*, 4, 1531-1545.
Huntington, T.G. (2010). Climate Warning-Induced Intensification of the Hydrological Cycle: An Assessment of the Published Record and Potential Impacts on Agriculture. *Advances in Agronomy*, 109, 1-53.
HWMC (Hydrology and Water Management Centre), http://www.hydro-4.com
Intasutra, T. (1983). Groundwater potential in unconsolidated Sedimetns in Chiang Mai Basin. *Proceedings of the First Symposium on Geomorphology and Quaternary Geology of Thailand*, Bangkok, Thailand, 28-29/10/1983, 179-195.
IPCC (2001). Climate Change 2011: The Scientific Basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. & Johnson, C.A. (eds.). *Cambridge University Press*, Cambridge, United Kingdom & New York, 881p.
IPCC (2007). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Pachauri, R.K. & Reisinger, A. (eds.). *IPCC*, Geneva, Switzerland, 104p.
IPPC (2014). Climate Change 2014 Synthesis Report. Contributions of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, Pachauri, R.K. & Meyer, L.A. (eds.). *IPCC*, Geneva, Switzerland, 151p.
Itayama, T., Hawkins, P.R., Leelahakrienkrai, P., Kullasoot, S., Whangchai, N., Chitmanat, C., Peerapornpisal, Y. & Kawabata, Z. (2015). Bioassessment of Dry Season Water Quality in the Ping River around Chiang Mai City, Thailand. *Chiang Mai Journal of Science*, 42(2), 349-366.
Jarungrattanapong, R. & Manasboonphempool, A. (2009). Adapting to Floods in Chiang Mai: Confronting the Gaps. *EEPSEA Climate Change Policy Brief*, No.2010CC-PB6, 4p.
Jarungrattanapong, R. & Manasboonphempool, A. (2011). Adaptive Capacity of Households and Institutions in Dealing with Floods in Chiang Mai, Thailand. *EEPSEA Research Reports*, No.2011-RR2, 60p
Jompakdee, W. (2004). Rivers in Jeopardy and the Role of Civil Society in River Restoration: Thai Experiences. *Chiang Mai University Journal*, 3(1), 59-71.
Junkhiwaw, S., Sinvongs, W., Sukhapunnaphan, T. & Tangtham, N. (2004). Developing Food Warning System for Upland Watersheds of the Chao Phraya Basin. *The Sixth International Study Conference on GEWEX in Asia and GAME*, Kyoto, Japan.
Kamdee, K., Corcho Alvarado, J.A., Occarach, O., Hunyek, V., Wongsit, A., Saengkorakot, C., Chanruang, P., Polee, C., Khaweerat, S., Matiatos, I. & Matsumoto, T. (2020). Application of Isotope Techniques to Study Groundwater Resources in the Unconsolidated Aquifers along the Ping River (Thailand). *Isotopes ini Environmental and Health Studies*, 1739672, 16p.
Kazmer, M., Sanitham, K., Charusiri, P. & Pailoplee, S. (2011). Archaeoseismology of the AD 1545 Earthquake in Chiang Mai, Northern Thailand. *@nd INQUA-IGCP 567 International Workshop on Active Tectonics, Earthquake Geology, Archeology and Engineering*, Corinth, Greece.
Modern Flood Event: The Mae Chaem River, Thailand. *In:* Thorndycraft, V.R., Benito, G., Barriendos, M. & Llasat, M.C. (2003). Palaeofloods, Historical Floods and Climatic Variability:

Applications in Flood Risk Assessment. *Proceedings of the PHEFRA Workshop, Barcelona, 16-19/10/2002*. 6p.
Kidson, R., Richards, K.S. & Carling, P.A. (2005). Reconstructing the ca. 100-year Flood in Northern Thailand. *Geomorphology*, 70, 279-295.
Kidson, R., Richards, K.S. & Carling, P.A. (2006). Power-Lae Extreme Flood Frequency. *In.* Cello, G. & Malamud, B.D. (2006). Fractal Analysis for Natural Hazards. *Geological Society, London, Special Publications*, 261, 141-153.
Komsai A., Kinouchi, T. & Wei, L.-Z. (2016). Simulation of Extreme Flood and Inundation in 2011 in the Upper Ping River Basin, Thailand. *Journal of Japan Society of Civil Engineers, Series B1 (Hydraulic Engineering)*, 72(4), 1183-1188.
Kripalani, R.H. & Kulkarni, A. (1997). Rainfall Variability Over South-East Asia – Connections with Indian Monsoon and ENSO Extremes: New Perspectives. *International Journal of Climatology*, 17, 1155-1168.
Kumcumphet, P. (2007). Guidelines for Flood Protection in Nakhon Chiang Mai Municipality, *M.Sc. Thesis*, Bangkok, Chulalongkorn University.
Kuraji, K., Punyatrong, K., Sirisaiyard, I., Tnatasirin, C. & Tanaka, N. (2007). Scale Dependency of Hydrological Characteristics in the Upper Ping River Basin, Northern Thailand. *In:* Sawada, H., Araki, M., Chappell, N.A., LaFrankie, J.V. & Shimizu, A. (eds). Forest Environments in the Mekong River Basin. *Springer, Tokyo*, 66-74.
Laonamsai, J., Julphunthong, P., Saprathet, T., Kimmany, B., Ganchanasyragit, T., Chomcheawchan, P. & Tomun, N. (2023). Utilizing NDWI, MNDWI, SAVI, WRI, and AWEI for Estimating Erosion and Deposition in Ping River in Thailand. *Hydrology*, 10(70). 25p.
Lebel, L., Foran, T., Garden, P. & Manuta, J.B. (2007). Adaptation to Climate Change and Social Justice: Challenges for Flood and Disaster Management in Thailand. *In.* Ludwig, F., Kabat, P., van Schaik, H. & van der Valk, M. (2009) Climate Change Adaptation in the Water Sector, *Routledge eds.*
Lebel, L., Garden, P., Subsin, N. & Na Nan, S. (2009). Averted Crises, Contested Transitions: Water Management in the Upper Ping River Basin, Northern Thailand. *In.* Huitema, D. & Meijerink, S. (eds.), *Edward Elgar Publishing Limited*, Water Policy Entrepreneurs. 137-157.
Leblond, J.-P. (2010). Population Displacement and Forest Management in Thailand. *ChATSEA Working Papers*, 8, Montreal.
Leelahakrienkrai, P. & Peerapompisal, Y. (2010). Diversity of Benthic Diatoms and Water Quality of the Ping River, Northern Thailand. *EnvironmentAsia*, 3(1), 82-94.
Lerdthusnee, S., Ramingwong, T. & Wattananikorn, K. (1981). Hydrogeochemistry of Groundwaters in the Vicinity of the City of Chiang Mai, Thailand.
Lim, H. S. & Boochabun, K. (2012). Flood Generation during the SW Monsoon Season in Northern Thailand. *In.* Terry, J.P. & Goff, J. (eds.) (2012). Natural Hazards in the Asia-Pacific Region: Recent Advances and Emerging Concepts. *Geological Society, London, Special Publications*, 361, 7-20.
Lim, H. S., Boochabun, K. & Ziegler, A.D. (2012). Modifers and Amplifiers of High and Low Flows on the Ping River in Northern Thaialnd (1921-2009): The Roles of Climatic Events and Anthropogenic Activity. *Water Resources Management*, s11269-012-0140-z, 24p.
Man, S. & Visessri, S. (2022). Low-Flow Assessment Methods for Ungauged Sub-Basins in the Upper Ping River Basin, Thailand. *Naresuan University Engineering Journal*, 18(1), 1-13.
Manopiniwes, W. & Irohara, T. (2016). Stochastic Optimisation Model for Intergrated Decisions on Relief Supply Chains: Preparedness for Disaster Response. *International Journal of Production Research*, 1211340, 19p.
Manopiniwes, W. & Irohara, T. (2020). Optimization Model for Temporary Depot Problem in Flood Disaster Response. *Natural Hazards*, 105, 1743-1763.

Manuta, J. & Lebel, L. (2005). Climate Change and the Risks of Flood Disasters in Asia: Crating Adaptive and Just Institutions. *In:* Human Security and Climate Change. An International Workshop, 21-23/06/2005, Oslo.
Manuta, J., Khrutmuang, S., Huaisai, D. & Lebel, L. (2006). Institutionalized Incapacities and Practice in Flood Disaster Management in Thailand. *Science And Culture*, Jan-Feb 2006, 10-22.
Mapiam, P. P., Sharma, A. & Sriwongstianon, N. (2014). Defining the Z-R Relationship using Gauge Rainfall with Coarse Temporal Resolution: Implications for Flood Forecast. *Journal of Hydrologic Engineering*, 19(8), 04014003.
Mapiam, P. P. & Sriwongsitanon, N. (2008). Climatological Z-R Relationship for Radar Rainfall Estimation in the Upper Ping River Basin. *ScienceAsia*, 34, 215-222.
Mapiam, P. P. & Sriwongsitanon, N. (2009). Estimation of the URBS Model Parameters for Flood Estimation of Ungauged Catchments in the Upper Ping River Basin, Thailand. *ScienceAsia*, 35, 49-56.
Mapiam, P. P. & Chautsuk, S. (2018). Improving Runoff Estimates by Increasing Catchment Subdivision Complexity and Resolution of Rainfall Data in the Upper Ping River Basin, Thailand. *Chiang Mai University Journal of Natural Sciences*, 17(2), 127-143.
Margane, A. & Tatong, T. (1999a). Aspects of the Hydrogeology of the Chiang Mai-Lamphun Basin, Thailand that are Important for Groundwater Management. *Zeitschrift für Angewandte Geologie*, 45(4), 188-197.
Margane, A. & Tatong, T. (1999b). Hydrogeology of the Chiang Mai – Lamphun Basin. *Proceedings of the International Conference on Water Resources Management in Intermontane Basin*, 2-6/02/1999. 151-166
McCarthy, J. F. (1888). Map of the Kingdom of Siam and Its Dependencies. (1900) eds. ChiangMai
McGrath, B., Sangawongse, S., Thaikatoo, D. & Corte, M. B. (2017). The Architecture of the Metacity: Land use Change, Patch Dynamics and Urban Form in Chiang Mai, Thailand. *Urban Planning*, 2(1), 53-71.
Molle, F. (2007). Irrigation and Water Policies: Trends and Challenges. *In*: Lebel, L., Dore, R., Daniel. R. & Koma, Y.S. (eds.) *Democratizing Water Governance in the Mekong Region*, Chiang Mai, Mekong Press, 9-36.
Mostafanezhad, M. & Evrard, O. (2021). Chronopolitics of Crisis: A Historical Political Ecology of Seasonal Air Pollution in Northern Thailand. *Geoforum*, 124, 400-408.
Mungsunti & Parton, 2017
Ng, S., Wood, S. H. & Ziegler, A. D. (2015). Ancient Floods, Modern Hazards: the Ping River, Paleofloods and the 'Lost City' of Wiang Kum Kam. *Natural Hazards*, s11069-014-1426-7, 17p.
Nid, S.H. (1989). The Contemporary Thai City as an Environmental Adaptation. *In*: Culture and Envrionment in Thailand: A Symposium on the Siam Society. *Siam Society*, Bangkok, 371-392.
Ninprom, S. & Chumchean, S. (2009). Effectiveness of Bias Adjustment Technique to Reduce Errors in MM5 Rainfall Forecasting on Flood Forecating Results of the Upper Ping River Basin. *The 14th National Convention on Civil Engineering*, Suranaree University of Technology, Nakhon Ratchasima.
Norse, D. (2003). Climate Change and Agriculture: Physical and Human Dimensions. *In*: Bruinsma, J. (eds.) *World Agriculture: Toward 2015/30 – An FAO Perspective*, FAO, Rome and Earthscan, London. 357-572.
Ogata, F., Saenjum, C., Nagahashi, E., Kobayashi, Y., Nakamura, T. & Kawasaji, N. (2020). Determining of the Water Quality of the Ping River at Different Seasons in Northern Thailand. *Chemical Pharmacological Bulletin*, 68(6), 546-551.
ONEP, Office of Natural Resources and Environmental Policy and Planning), 2006. The State of the Environment. Ministry of Natural Resources and Environment, Bangkok, Thailand.

Ongsakul, S. (2005). History of Lanna. *Silkworm Books*, Chiang Mai.
Patsinghasanee, S. (2004). Performance Comparison of Artificial Neural Network and Hydrodynamic Models on Flood Forecasting in the Upper Ping River Basin. *M.Sc. Department of Water Resources Engineering*, Bangkok, *Kasertsart University*.
Patsinghasanee, S., Lipiwattanakam, S. & Sriwongsitanon, N. (2004). An Optimized Back Propagation Neural Network for Flood Forecasting in the Ping River. *The 9th National Convention on Civil Engineering*. Thailand.
Peng, S., Piao, S., Ciais, P., Myneni, R.B., Chen, A., Cevallier, F., Dolman, A. J., Janssens, I.A., Penuelas, J., Zhang, G., Vicca, S., Wan, S., Wang, S. & Zeng, H. (2013). Asymmetric Effects of Daytime and Night-Time Warning on Northern Hemisphere Vegetation. *Nature*, 501, 88-92.
Penth, H. (2004). A Brief History of Lan Na: Northern Thailand from Past to Present. *Silkworm Books*, Chiang Mai.
Pholkern, K., Srisuk, K., Grischek, T., Soares, M., Schafer, S., Archwichai, L., Saraphirom, P., Pavelic, P. & Wirojanagud, W. (2015). Riverbed Clogging Experiments at Potential River Bank Infiltration Sites along the Ping River, Chiang Mai, Thailand. *Environmental Earth Sciences*, 73, 7699-7709.
Phongpanich, N., Guang-Guay, M. & Tsair-Bor, Y. (2014). Climate Change Impact on Agricultural Products in Thailand: A Case Study of Thai Rice at the Chao Phraya River Basin. *APCBEE Procedia*, 8, 136-140.
Pirard, C. & Charoenpanwutikul, A. (2023). Comprehensive Review of the Annual Haze Episode in Northern Thailand. *EarthArXiv*, X5509C, 141p.
Pitrakul, S. & Uttamo, W. (1987). Why did Wiang Kum Kam Disappear from History Pages 400 Years Ago? A Geological Evidence. *Lanna Studies Bulletin*, 2(4), 5-13.
Promping, T., Ang, R., Win, S. & Pratopo, K. (2019). Application of HEC-RAS Model for Introducting Flood Mitigation Measures at the Upper Ping River, Chiang Mai City. *International Sustainable Development Studies Institute, Chiang Mai*, 3-28/06/2019.
Proverbs, D., Mambretti, S., Brebbia, C.A. & de Wrachien, D. (eds). (2012). Flood Recovery, Innovation and Response III. *WIT Transactions on Ecology and The Environment*, 159,
Puttaraksa, P., Sriwongsitanon, N. & Lipiwattanakarn, S. (2005). Development of One Dimensional Implicit Dynamic Wave Model. *KKU Engineering Journal*, 32(1), 31-48.
Rangsiwanichpong, P. & Melesse, A. M. (2022). Analyzing the Benefit-Cost Ratio of Sediment Resources by Remote Sensing Data in the Ping River Basin, Thailand. *Water*, 14, 2071, w14132071, 16p.
Rasmusson, E.M. & Carpenter, T.H. (1983). The Relationship between Eastern Equatorial Pacific Sea Surface Temperatures and Rainfall over India and Sri Lanka. *Monthly Weather Review*, 111, 517-528.
Reda, A. G., Tripathi, N. K., Soni, P., Tipdecho, T. & Vaddhanaphuti, C. (2012). Climate Variability in Ping River Basin, Northern Thailand. *4th International Conference of GIT4NDM*, 7-8/11/2012, 8p.
Reda, A. G., Tripathi, N. K., Soni, P., Tipdecho, T. & Phalke, A. (2013). Temporal Climate Trend of Ping Basin of Thailand and Implications for Mekong Region. *Journal of Earth Science & Climatic Change*, 4(4), 1000146, 8p
Reda, A. G., Tripathi, N. K. & Mozumder, C. (2014). Agricultural Landuse Changes under Climate Variability in Thailand. *Open Science Repositery Agriculture*, 17p
RID, Royal Irrigation Department. www.rid.go.th
Rigg, J. & Nattapoolwat, S. (2001). Embracing the Global in Thailand: Activism and Pragmatism in an Era of Deagrarianization. *World Development*, 29(6), 945-960.

Rodratana, P. & Piamsa-Nga, N. (2008). The Study of Flood Alleviation of Chiang Mai City Area. *The 13th National Convention on Civil Engineeering*, Pattaya, Thailand.
Ropelewski, C. F. & Halbert, M.S. (1987). Global and Regional Scale Precipitation Associated with ENSO. *Monthly Weather Reviews*, 115, 1606-1626.
Saengsawang, S., Pankhao, P., Kaprom, C. & Sriwongsitanon, N. (2017). Projections of Future Rainfall for the Upper Ping River Basin using Regression-based Downscaling. *Advances in Climate Change Research*, 8, 256-267.
Saenton, S. (2010). Applications of Stochastic Process and Inverse Modeling Technique in Groundwater Modeling of the Chiang Mai Basin. *Thailand Research Fund Final Report*, Bangkok.
Sangawongse, S. (2006). Land-use/Land-cover Dynamics in Chiang Mai: Appraisal from Remote Sensing, GIS and Modeling Approaches. *CMU Journal*, 5(2), 243-254.
Sangawongse, S., Fisher, R. & Prabudhanitisarn, S. (2021). Form Centralised Planning to Collaborative Urban Land Use Planning: The Case of Wat Ket, Chiang Mai, Thailand. *Social Sciences & Humanities Open*, 4, 100154, 10p.
Schreider, S.Y., Jakeman, A.J., Gallant, J. & Merritt, W.S. (2002). Prediction of Monthly Discharge in Ungauged Catchments under Agricultural Land Use in the Upper Ping Basin, Northern Thailand. *Mathematicas and Computers in Simulation*, 59, 19-33.
Sektheera, R. & Thodey, A.R. (1974)). Irrigation Systems in the Chiang Mai Valley Organization and Management. *Chiang Mai Faculty of Agriculture*, Chiang Mai University.
Sharma, D., Das Gupta, A. & Babel, M. S. (2007). Spatial Disaggregation of Bias-Corrected GCM Precipitation for Improved Hydrological Simulation. Ping River Basin, Thailand. *Hydrology and Earth System Sciences*, 11, 1373-1390.
Sharma, D. & Babel, M. S. (2013). Application of Downscaled Precipitation for Hydrological Cliamte-Change Impact Assessement in the Upper Ping River Basin of Thailand. *Climate Dynamics*, 41, 2589-2602.
Singhrattana, N., Rajagopalan, B., Kumar, K. K. & Clark, M. (2005a). Interannual and Interdecadal Variability of Thailand Summer Monsoon Season. *Journal of Climate*, 18, 1697-1708.
Singhrattana, N., Rajagopalan, B., Clark, M. & Kumar, K. K. (2005b). Seasonal Forecasting of Thailand Summer Monsoon Rainfall. *International Journal of Climatology,* 25(5), 649-664.
Sophhonphattanakul *et al.*, 2009
Sriwongsitanon, N. (2010). Flood Forecasting System Development for the Upper Ping River Basin. *Kasetsart Journal (Natural Sciences)*, 44, 717-731.
Sriwongsitanon, N. & Taesombat, W. (2011). Estimation of the IHACRES Model Parameters for Flood Estimation of Ungauged Catchments in the Upper Ping River Basin. *Kasersart Journal (Natural Sciences)*, 45, 917-931.
Sutiwanich, C., Phienwej, N., Harnpattanapanich, T., Fasching, A. & Laubblishler, K. (2006). Investigation and Preliminary Desing of Mae Ngat-Mae Kuang Tunnel Chiang Mai Province, Thailand. *Panya Consultants Co.*
Sukka, P. (2005). Forecasting of Daily Inflow to Large Reservoir in Upper Ping River Basin using Artificial Neural Network. *M.Sc.*, *Civil Engineering*, Chiang Mai, Chiang Mai University.
Suphawan, K. & Chaisee, K. (2021). Gaussian Process Regression for Predicting Water Quality Index: A Case Study on Ping River Basin, Thailand. *AIMS Environmental* Science, 8(3), 268-282.
Suvagondha, F. (1979). Hydrogeology of Amphoe Muan Lamphun. *M.Sc. Chiang Mai*, Chiang Mai University.
Swearer, D.K. & Premchit, S. (1998). The Legend of Queen Cama: Bodhiramsi's Camaldevivamsa, a Translation and Commentary. *University of New York Press.* Albany, New York.

Tachaudmondach, S., Upayokin, A., Kronprasert, N. & Arunotayanun, K. (2021). Quantifying Road-Network Robustness Towards Flood-Resilient Transportation Systems. *Sustainability*, 13, 3172, 16p.
Taesombat, W. & Sriwongsitanon, N. (2010). Flood Investigation in the Upper Ping River Basin Using Mathematical Models. *Kasetsart Journal (Natural Sciences)*, 44, 152-166.
Taesombat & Sriwongsitanon, 2006
Tan Kim Yong, U. (1983). Resource Mobilization in Traditional Irrigation Systems of Northern Thailand: A Comparison between the Lowland and the Upland Communities. *New York, Cornell University.*
Tan Kim Yong, U., Bruns, P.C. & Bruns, B.R. (2005). Ther Emergence of Polycentric Water Governance in Northern Thailand. *In:* Shivakoti, G.P., Vermillion, D.L., Lam, W.-F., Ostrom, E., Pradhan, U. & Yoder, R. (eds.) *Asian Irrigation in Transition: Responding to Challenges. London, Sage Publications*, 226-252.
Tansar, H., Akbar, H. & Aslam, R. A. (2021). Flood Inundation Mapping and Hazard Assessment for Mitigation Analysis of Local Adaptation Measures in Upper Ping River Basin, Thailand. *Arabian Journal of Geosciences*, 14, 2531.
Tatong, T., Chatprasert, S., Kunthacap, P. & Neumann-Redlin, C. (1997). Compilation of Hydrogeological Data for Thematic Maps in the Chiang Mai – Lamphun Basin (N-Thailand). *Academic Conference to the Geology Division, 22-23/12/1997*, 4p.
Taweelarp, S., Khebcharoen, M. & Saenton, S. (2021). Evaluation of Groundwater Potential and Safe Yield of Heterogenoeus Unconsolidated Aquifers in Chiang Mai Basin, Northern Thailand. *Water*, 13, 558, 26p
Teo, E. A. (2018). Ping River Palaeochannels A Review of Evidence across Historical Literature, Archaeology and Geoscience. *Chiang Mai University of Social Sciences and Humanities*, 5(1), 32p.
Thaisawadi, O., Sriwongsitanon, N. & Lipiwattanakam, S. (2007). Daily Flow Estimation for Small Ungauged Basins Using Artificial Neural Network Models. *The 12th National Convention on Civil Engineering*, Phitsanulok, Thailand
Thomas, D., Weyerhaeuser, H. & Saipathong, P. (2002). Improved Tools for Managing Agroforestry Landscapes in Northern Thailand: Pilot Application of Spatial Analysis and Negotiation Support Systems. *In:* Landscapes of Diversity: Indigenous Knowledge, Sustainable Livelihoods and Resource Governance in Montane Mainland Southeast Asia. Jianchu, X. & Mikesell, S. (eds.). *Proceedings of the 3rd Symposium on MMSEA*, 25-28/08/2002. Lijiang, China.
Tikul, N. (2018). Low Income Housing Adaptation Strategies to Flood Hazard in Chiang Mai, Thailand. *Journal of Thai Interdisciplinary Research*. 13(5), 19-26.
Tingsanchali, T. & Gautam, M.R. (2000). Application of Tank, NAM, ARMA and Neural Network Models to Flood Forecasting. *Journal of Hydrological Processes*, 14, 2473-2487.
Tingsanchali, T.S. & Rewtrakulpaiboon, L. (2003). Institutional Arrangements for Flood Disaster Management in Thailand. Strengthening Regional Capacity through Best Practices in Integrated Water Resources Management. *Proceedings Volume 2. Technical Papers*, 1st SouthEast Asia Water Forum, 17-21/11/2003, Chiang Mai, Thailand.
Trenberth, K.E. (2011). Changes in Precipitation with Climate Change. *Climate Research*, 47, 123-138.
Triritthwittaya, P., Ekkawatpanit, C., Kositgittwong, D. & Kompor, W. (2022). The Estimation of Sediment Dynamics in Mae Chaem River Basin Using SWAT Model. *The 27th National Convention on Civil Engineering.* 24-26/08/2022, Chiang Rai, Thailand.
Ueangsawat, K. & Jintrawet, A. (2013). The Impacts of ENSO Phases on the Variation of Rainfall and Stream Flow in the Upper Ping River Basin, Northern Thailand. *Environment and Natural Resources Journal*, 11(2), 97-119.

Ueangsawat, K. & Jintrawet, A. (2014). An Assessement of Future Climate Change and Water Condition in Upper Ping River Basin under A2 and B2 Scenarios during 2015-2074. *Environment and Natural Resources Journal*, 12(1), 22-43.
UNOSAT (United Nations Satellite Centre). (2024). Flood FL202409112THA Preliminary Report. 1p.
Uppasit, S. (2004). Groundwater Recharge Calculation of Chiang Mai Basin Using Water-Table Fluctuation Method. *M.Sc. Thesis*, Chiang Mai University, Chiang Mai, Thailand.
Vandergeest, P. & Peluso, N.L. (1995). Territorialization and State Power in Thailand. *Theory and Society*, 24, 385-426.
van Dijk, A.I.J.M, van Noordwijk, M., Calder, I.R., Bruijnzeel, L.A., Schellekens, J. & Chappell, N. (2009). Forest-Flood Relation Still Tenuous – Comment on Bradshaw, C.J.A., Sodi, N.S., Peh, K.S.H. & Brook, B.W. (2009). Global Evidence that Deforestation Amplifies Flood Risk and Severity in the Developing World. *Global Change Biology*, 15, 110-115.
Velechovsky, M., Sinthusan, A. & Pitragool, S. (1987). Geological Aspects of the Burial by Flood of the Ancient City of Wiang Kum Kam, Chiang Mai, Thailand. *Unpublished Report*, Center for the Promotion of Arts and Culture, Chiang Mai University. 18p.
Vichit-Vadakan, J. (1989). Thai Social Structure and Behavior Patterns: Nature versus Cutlure. *In:* Culture and Environment in Thailand: A Symposium of the Siam Society. *Siam Society*, Bangkok, 425-448.
Vongtanaboon, S., Lim, H. S. & Richards, K. (2008). Data-Based Mechanistic Rainfall-Runoff Modelling for a Large Monsoon-Dominated Catchment in Thailand. *Silpakorn University Sciecne & Technology Journal*, 2(1), 14-28.
Walker, A. (2002). Forests and Water in Northern Thailand. *RMAP Working Paper 37*, Resource Management in Asia Pacific Programme, The Australian National University.
Walker, A. (2003). Agricultural Transformation and the Politics of Hydrology in Northern Thailand. *Development and Change*, 34(5), 941-964.
Walker, A. (2004). Seeing Famers for the Trees Community Forestry and the Arborealisation of Agriculture in Northern Thailand, *Asia Pacific Viewpoint*, 45, 311-324.
Wattananikorn, K., Beshir, J.A. & Nochaiwong, A. (1995). Gravity Interpretation of Chiang Mai Basin, Northern Thailand: Concentrating on Ban Thung Sieo Area. *Journal of SouthEast Asian Earth Sciences*, 12, 53-64.
Weesakul, U., Luangdilok, N. & Keawsawasvong, S. (2022). Interpretation Physical Meaning of Meteorological Drought Indicators: A Case Study in Ping River Basin, Thailand. *Journal of Applied Science and Engineering*, 26(9), 1271-1283.
Wilk, J., Andersson, L. & Plemkanon, V. (2001). Hydrological Impacts of Forest Conversion to Agriculture in a Large River Basin in Northeast Thailand. *Hydrological Processes*, 15, 2748-2759
Wood, S.H. & Ziegler, A.D. (2007). Floodplain Sediment from a 30-year Recurrence Flood in 2005 of the Ping River in Northern Thailand. *Hydrology and Earth Systems Sciences*, 4, 3839-3868.
Wood, S.H. & Ziegler, A.D. (2008). Floodplain Sediment from a 100-year Recurrence Flood in 2005 of the Ping River in Northern Thailand. *Hydrology and Earth Systems Sciences*, 12, 959-973.
Wood, S.H., Liberty, L.M., Singharajwarapan, F. S., Bundarnsin, T. & Rothwell, E. (2004). Feasibility of Gradient Magnetometer Surveys of Buried Brick Structures at 13th Century (C.E.) Wiang Kum Kam, Chiang Mai Province, Thailand. *International Conference on Applied Geophysics*, 26-27/11/2004, Chiang Mai, Thailand. 22-30.
World Bank, 2006
Wuthiwongyothin, S., Jang, S.-H., Ishida, K. & Kavvas, M.L. (2017). The Effects of Climate Change on Hydrology based on Dynamically Downscaling and Physically-based Hydrology Model

at Upper Ping River Basin, Thailand. *International Journal of Society for Social Management Systems*, 11(1), 78-89.
Wuthiwongyothin, S., Mili, S. & Phadunkarnlert, N. (2019). A Study of Correcting Climate Model Daily Rainfall Product using Quantile Mapping in Upper Ping River Basin, Thailand. *Proceedings of the 10th International Conference on Asian and Pacific Coasts (APAC 2019)*, Hanoi, Vietnam, 25-28/09/2019. 1213-1214.
Wuthiwoongtyohtin, S. (2021). Investigating Statistical Bias Correction with Temporal Subsample of the Upper Ping River Basin, Thailand. *Journal of Water and Climate Change*, 12(5), 1631-1653.
Wyatt, D.K. & Wichienkeeo, A. (1995). The Chiang Mai Chronicle. *Silkworm Books*, Chiang Mai.
Yongsiri, P., Soytong, P., Laongmanee, W. & Uthaisri, P. (2023). Development of a Landslide Risk Area Display System by using the Geospatial Technology with Daily Rainfall Data via the Internet Network in the Northern Region of Thailand. *International Journal of Agriculutral Technology*, 19(4), 1953-1968.
Yotapakdee, T. & Havrland, B. (2012). The Impact Assesement of Water Resource Management in Rainfed Area in the Upper Ping River Basin, Chiang Mai, Thailand. *International Journal of Environmental Science and Development*, 3(2), 99-102
Ziegler *et al.*, 2001
Ziegler, A.D., Lim, H. S., Tantasarin, C., Jachowski, N. R. & Wasson, R. (2012). Floods, False Hope and the Future. *Hydrological Processes*, hyp.9260, 3p.