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TOPICAL REVIEW

A review of climate-change impact and adaptation studies for the water sector in Thailand

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Abstract

Thailand plays a central economic and policy-making role in Southeast Asia. Although climate change adaptation is being mainstreamed in Thailand, a well-organized overview of the impacts of climate change and potential adaptation measures has been unavailable to date. Here we present a comprehensive review of climate-change impact studies that focused on the Thai water sector, based on a literature review of six sub-sectors: riverine hydrology, sediment erosion, coastal erosion, forest hydrology, agricultural hydrology, and urban hydrology. Our review examined the long-term availability of observational data, historical changes, projected changes in key variables, and the availability of economic assessments and their implications for adaptation actions. Although some basic hydrometeorological variables have been well monitored, specific historical changes due to climate change have seldom been detected. Furthermore, although numerous future projections have been proposed, the likely changes due to climate change remain unclear

due to a general lack of systematic multi-model and multi-scenario assessments and limited spatiotemporal coverage of the study area. Several gaps in the research were identified, and ten research recommendations are presented. While the information contained herein contributes to state-of-the-art knowledge on the impact of climate change on the water sector in Thailand, it will also benefit other countries on the Indochina Peninsula with a similar climate.

1. Introduction

Climate change is an urgent global environmental concern that can be resolved only under an international framework, with regional effects that can be tackled only through region-specific approaches. In their Fifth Assessment Report (AR5), Working Group II of the Intergovernmental Panel on Climate Change (IPCC) summarized the state-of-the-art knowledge on the vulnerability and exposure of human and natural systems to climate change, the observed impacts and future risks of climate change, and the potential for and limits to adaptation (Field *et al* 2014). The IPCC noted a general lack of case studies on adaptation to climate change that consider local characteristics, particularly for middle-income and developing countries recognized as vulnerable.

Thailand plays a central economic and policy-making role in Southeast Asia. Thailand is the second largest economy in Southeast Asia after Indonesia (https://databank.worldbank.org/source/world-development-indicators), and therefore influences the development of neighboring countries. To tackle projected climate-change impacts, the Thai government's Office of Natural Resource and Environmental Policy and Planning (ONEP) formulated a Climate Change Master Plan in 2015 and a National Adaptation Plan (NAP) in 2019. The ONEP is now actively working on NAP guidelines that include details on the implementation of adaptation measures by municipal and operational agencies (ONEP 2015). Adaptation is being mainstreamed in Thailand, and the results of earlier climate-change impact and adaptation studies have been disseminated. However, to the authors' knowledge, a comprehensive review of the scientific literature on climate-change impacts on the water sector in Thailand has yet to be conducted.

Therefore, in the first systematic literature review of this topic, we focused on meteorology and six water-related sub-sectors: riverine hydrology, sediment erosion, coastal erosion, forest hydrology, agricultural hydrology, and urban hydrology. The review covers earlier studies, conducted over several decades, of climate-change impacts in Thailand. It includes not only papers published in international journals but also important contributions written in Thai, as well as influential governmental reports. The key questions answered by this review are: Are there historical data on the key variables in each sub-sector? What changes have occurred? What kind of climate-change impact studies have been conducted so far

and what were their key results? Have studies on economic assessments and adaptation measures been conducted? While writing this review, we noticed that these questions have only been partially and indirectly answered in scientific publications. Therefore, we also tried to identify and discuss the major gaps in this field of research.

Our literature survey was conducted as follows. Papers in the Web of Science were systematically surveyed in a search using the keywords listed in table 1 for the field 'topics.' From the titles and abstracts of the search results, relevant papers were identified. The regions of the target areas were also identified for each contribution. Based on expert opinion, the most important papers were considered and their key results are introduced in sections 3 and 4. To ensure a comprehensive and informative review, papers not included in the database were added according to expert opinion.

To cover this extensive research field, the framework of an ongoing research project, entitled 'Advancing Co-design of Integrated Strategies with Adaptation to Climate Change in Thailand,' (ADAP-T), was fully utilized. ADAP-T is a bilateral, collaborative research program between Thailand and Japan. Launched in 2016, it has over 100 members from numerous universities, governmental agencies, and other organizations of both countries. The primary aim of ADAP-T is to provide quantitative projections of climate-change impacts on Thailand for the above-mentioned six water sub-sectors, by applying the latest modeling techniques. This article was jointly prepared by Japanese and Thai scientists in conjunction with practitioners from academic institutions and responsible agencies on climate-change impacts in Thailand (see Authors' contributions). To reduce bias, at least two authors wrote and edited each sub-sector. In addition, the opinions of 25 leading experts in Thailand were obtained through consultation at 'The Workshop on Climate Change Impact and Adaptation Studies for the Water Sector in Thailand,' held in Bangkok on 11 March 2019. The results and recommendations of this workshop have been incorporated into this review.

Following this Introduction, section 2 describes the geography and hydrometeorology of Thailand as well as the relevant governmental organizations. Section 3 introduces the observed and projected changes in meteorology. Section 4 details the impact assessments and risk evaluations of climate change for the six water-related sub-sectors, while section 5

Table 1. The numbers of papers in each region for each sector in the search results using the web of science and the keywords for the 'Topics' field. The relevant papers were selected and the target areas were identified based on their titles and abstracts. Double-counted papers between the search results of (a) and (b) were subtracted.

Sector	Riverine hydrology	Sediment	Coastal erosion	Forest hydrology	Agricultural hydrology	Urban hydrology
Keywords[a]	(a) Discharge (b) Streamflow	(a) Landslide (b) Slope failure	(a) Coastal erosion (b) Shoreline change	(a) Deforestation (b) Land use, hydrology	(a) Rice yield (b) Irrigation	Urban
No. of papers in the search result	66	21	24	54	86	68
No. of relevant papers	50	12	6	28	61	25
Northern	15	3	0	7	7	0
Northeastern	6	0	0	3	16	1
Central	4	0	1	2	6	13
Eastern	1	0	0	1	0	0
Southern	0	4	1	0	1	0
Thailand	10	1	1	3	10	4
SE Asia	9	0	1	9	12	4
Asia	1	0	1	0	3	1
Global	4	4	1	3	6	2

[a] The keywords, 'Thailand' and 'climate change' were added in each search. Two sets of searches ((a) and (b)) were performed for each sector, except for the urban sector.

presents the results of a cross-sectoral analysis using the results reported in section 4. Research gaps and recommendations are compiled in section 6. Policy implications are presented in section 7 and concluding remarks constitute section 8.

2. Study area

2.1. Geography of Thailand

Thailand is located between latitudes 5°27′ N and 20°27′ N and longitudes 97°27′ E and 105°37′ E. The total land area of the country is 517 624 km^2. The coastline spans ∼3148 km, of which roughly 2055 km are along the Andaman Sea and 1093 km are along the Gulf of Thailand. There are 76 provinces ('*Changwat*' in Thai) and two special administrative areas, the capital (Bangkok Metropolitan Administration; BMA) and the city of Pattaya (figure 1(a)). The provinces are further divided into districts ('*Amphoe*'). According to the Department of Provincial Administration (2019), there are 878 districts in Thailand.

2.2. The climate of Thailand

The Thai climate is characterized by an annual cycle of wet and dry seasons, with most of the rainfall concentrated in the wet season, i.e. the summer monsoon season (Thai Meteorological Department 2015). The capital, Bangkok, has a rainy season that extends from mid-May to October, and a dry season from November to April (Vu *et al* 2016). The mean annual rainfall in Bangkok is 1437 mm, with an average maximum daily rainfall of between 78 and 112 mm (Klongvessa and Chotpantarat 2015). The average minimum temperature is approximately 20 °C and occurs between November and February, while the maximum temperature of ∼35 °C occurs between March and June (Shrestha *et al* 2017a).
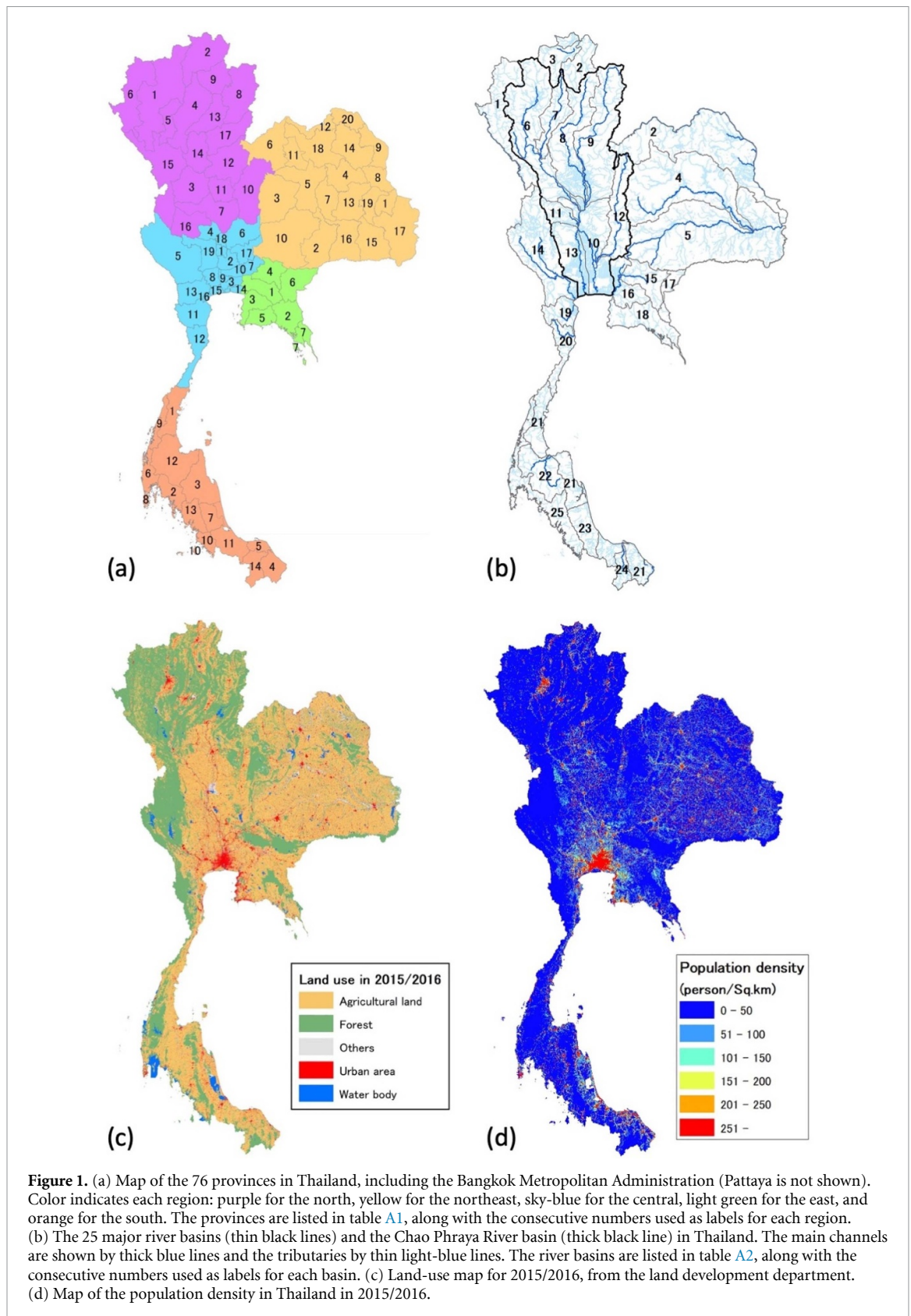
2.3. Rivers in Thailand

Thailand has 25 major river basins (figure 1(b)) and more than 250 sub-basins. The basins of the Chao Phraya and Mun rivers are the two largest river basins in Thailand. The Chao Phraya is the largest river in Thailand and its basin is the most populated. The 157 925 km^2 of the Chao Phraya basin cover some 30% of the country's area and extend across 29 provinces. The Chao Phraya river system consists of four principal tributaries: the Ping (36 018 km^2), the Wang (11 708 km^2), the Yom (24 720 km^2), and the Nan (34 557 km^2) rivers. These tributaries merge at the city Nakhon Sawan. Above (below) this point marks the upper (lower) Chao Phraya River. The Bhumibol Reservoir (capacity: 13 462 × 10^6 m^3) in the Ping river and the Sirikit Reservoir (capacity: 9510 × 10^6 m^3) in the Nan river, both operated by the Electricity Generating Authority of Thailand[26], are the largest. The Mun river basin covers the majority of northeast Thailand (119 180 km^2). The Mun river system consists of one principal tributary, the Chi river (49 480 km^2).

2.4. Land use and population in Thailand

The Land Development Department produces a nationwide land-use map once every 2 years that classifies land use into five major categories (level 1), which are subdivided into 33 classes (level 2). Major land-use categories include: agricultural land, forest

Figure 1. (a) Map of the 76 provinces in Thailand, including the Bangkok Metropolitan Administration (Pattaya is not shown). Color indicates each region: purple for the north, yellow for the northeast, sky-blue for the central, light green for the east, and orange for the south. The provinces are listed in table A1, along with the consecutive numbers used as labels for each region. (b) The 25 major river basins (thin black lines) and the Chao Phraya River basin (thick black line) in Thailand. The main channels are shown by thick blue lines and the tributaries by thin light-blue lines. The river basins are listed in table A2, along with the consecutive numbers used as labels for each basin. (c) Land-use map for 2015/2016, from the land development department. (d) Map of the population density in Thailand in 2015/2016.

land, urban and built-up land, water bodies, and miscellaneous. In 2015/2016, these land-use types accounted for 55%, 33%, 6%, 3%, and 3% of the land use in Thailand, respectively (figure 1(c)).

The total population in Thailand in 2018 was 66 413 979 people, according to the Department of Provincial Administration. The national average population density was 128 people km^{-2}. The highest density, 300 people km^{-2}, is in the central region, and the lowest, 72 people km^{-2}, is in the mountainous northern region. A map of the population density in 2015–2016 is provided in figure 1(d).
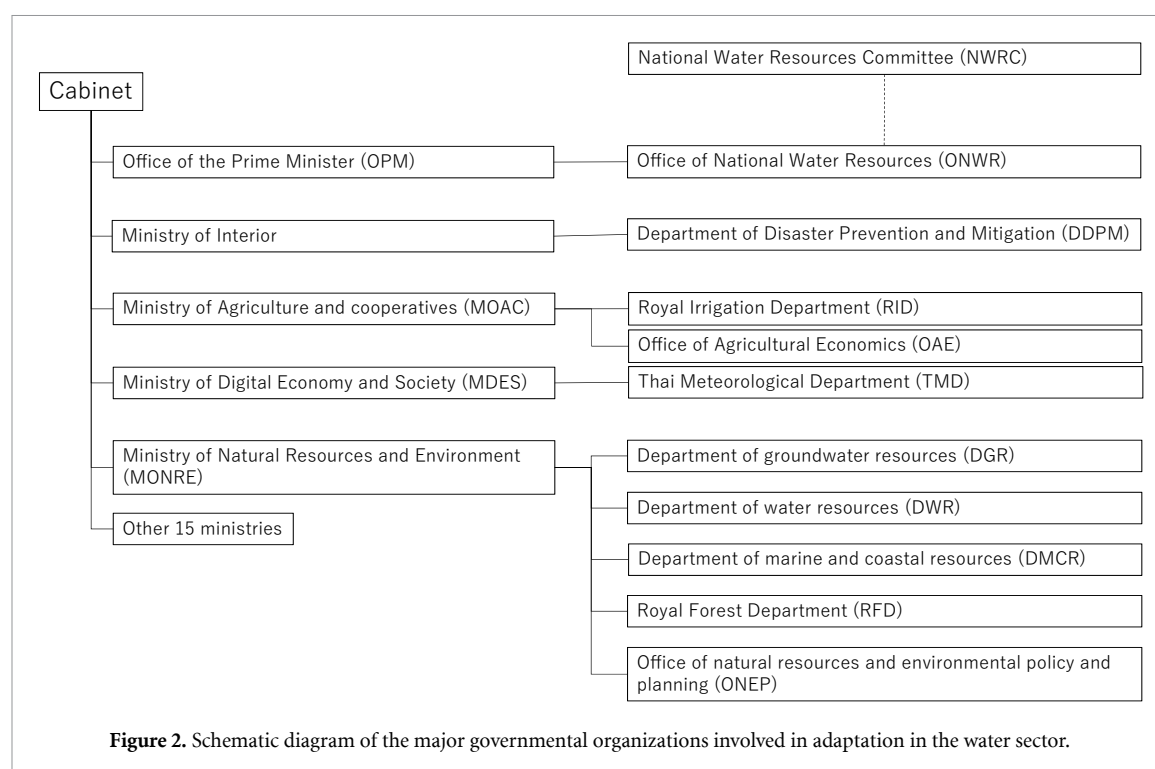
Figure 2. Schematic diagram of the major governmental organizations involved in adaptation in the water sector.

2.5. Governmental organizations

The Thai governmental organizations cited frequently in this review are listed in figure 2. The Thai Meteorological Department (TMD), which is under the Ministry of Digital Economy and Society, is in charge of meteorological observations, weather forecasting, weather-related hazard alarms, and meteorology-related data distribution. The Royal Irrigation Department of Thailand (RID), under the Ministry of Agriculture and Cooperatives, is responsible for developing water resources, managing water allocation, and preventing and mitigating water hazards. In 2002, the Ministry of Natural Resources and Environment (MoNRE) was created to oversee water-related organizations spanning many ministries and agencies. The MoNRE includes the Department of Groundwater Resources, which is responsible for the management of groundwater resources, and the Department of Water Resources (DWR), which is responsible for the management and maintenance of small- and medium-scale reservoirs and weirs to secure water resources and mitigate local flood/sediment disasters. The Office of National Water Resources is a regulatory agency established within the Office of the Prime Minister at the end of 2017 to unify cross-sectional water policy.

2.6. Climate policy

The National Economic and Social Development Board (NESDB) is a national economic planning agency in Thailand that issues a plan once every 5 years. The goal set out in the 11th NESDB (2012–2016) was to move Thailand towards being a low-carbon and climate-resilient society (National Economic and Social Development Board 2011).

After the plan was issued, the ONEP, under the MoNRE, formulated the Climate Change Master Plan 2015–2050 (ONEP 2015), under which the Climate Change Action Plan and the NAP were established.

The NAP requires every government agency to establish and implement an adaptation policy for the period 2018–2021. The six sectors targeted by the NAP are: water management, agriculture and food security, tourism management, public-health management, natural-resource management, and human settlement and security (Sakhakara, 2017, ONEP 2018a). The implementation process is expected to be completed by 2021. Eight international organizations and projects support ONEP activities related to the implementation process.

Thailand has established a National Committee on Climate Change as a coordination mechanism to address climate change at the national level. The committee is chaired by the Prime Minister and its members include ministries with policy-oriented interdepartmental roles as well as line-implementing agencies such as the ONEP, the Thailand Greenhouse Gas Management Organization, and the Overseas Development Institute (Overseas Development Institute 2012). The ONEP is the core agency responsible for issues and activities related to climate change (ONEP 2010).

Public expenditures related to climate change between 2009 and 2011 were spread over 137 governmental agencies and departments (total of 404), which were allocated budgets for climate-related programs. The climate budget represents around 2.7% of the government's total budget. The two main ministries involved in climate-related activities are the Ministry of Agriculture and Cooperatives (55%)

and MoNRE (29%) (Overseas Development Institute 2012).

3. Observed and projected meteorological changes

3.1. Introduction
Climatic and meteorological conditions are the starting point in assessment of the impacts of climate change. While recognizing the complexity of climate and meteorology, this section focuses primarily on air temperature and precipitation because these are the two most well-monitored parameters that are directly relevant to the water sector.

3.2. Historical analyses
3.2.1. Data availability
Data from the meteorological observations collected at 110 stations are publicly available at the TMD website in the form of summary reports compiled at daily, weekly, monthly and annual intervals[27]. The reports available for the periods are, however, limited, which has hampered analyses of the effects of climate change: annual reports are available for the years after 2013, monthly reports for the last year, and daily reports for the most recent 3 months. Daily data obtained by automatic weather systems are available beginning after 2007[28]. Requests for data not available on the website must be submitted to the TMD (see the Supplemental Material S1.1 for detail, which is available online at stacks.iop.org/ERL/16/023004/mmedia).

3.2.2. Observed temperature changes
According to the IPCC, the mean land-surface air temperature (hereafter temperature) in Southeast Asia over the last 100 years has increased by about 1 °C, similar to the observationally based trends determined in other areas at comparable latitudes (figure 2.21 of Hartmann *et al* 2013; figure 24-2 of Hijioka *et al* 2014). Acceleration of the mean annual temperature has been revealed by analyses of meteorological station datasets. Limjirakan and Limsakul (2012) estimated a mean temperature increase over the period 1970–2007 of 0.024 °C yr^{-1}, based on observations at 28 stations. In a 2018 TMD report (Thai Meteorological Department 2018) based on data from 45 weather stations, the temperature trend was shown to have increased since 1981 by $+0.014 \pm 0.031$ °C yr^{-1}.

Changes in temperature extremes have also been documented. Vongvisessomjai (2010) determined an increasing trend in annual maximum temperatures between 1951 and 2006. A large increase occurred in southern Thailand, moderate increases in eastern and northeastern regions of the country, and small

increases in its northern and central regions. In their analysis of the trends in extreme daily temperatures in western Thailand between 1961 and 2002, Sharma and Babel (2014) found statistically significant increasing trends in the annual numbers of warm days and warm nights, with corresponding decreasing trends in the annual numbers of cool days and cold nights. Cheong *et al* (2018) analyzed temperatures in Southeast Asia, including Thailand, and found an increasing trend in temperatures across the region during the period 1972–2010, particularly during warm nights.

3.2.3. Observed precipitation changes
An assessment of annual precipitation in Asia during the period 1951–2010 reported by the IPCC (figure 24-2 of Hijioka *et al* 2014) included a mixture of increasing and decreasing trends over Thailand, but none was statistically significant.

Mean annual precipitation in Thailand has been analyzed using meteorological station datasets, with many studies showing decreasing trends. Mean annual precipitation was analyzed by Vongvisessomjai (2010), who reported a decreasing trend in annual precipitation during the period 1951–2007 for the whole of Thailand. The decrease was largest in the eastern region, discernible in the southern region, but was only marginal in the central, northern, and northeastern regions. Sharma and Babel (2014) also found evidence of a decreasing trend in annual total precipitation over western Thailand during the period 1961–2002. Some studies have questioned the statistical significance of this trend. For example, according to the ONEP (2018b) there has been no significant long-term change in mean precipitation, although annual rainfall in Thailand has been characterized by marked short-term variations that correlate with the El Nino-Southern Oscillation and the Pacific Decadal Oscillation.

The majority of studies have reported a general trend of wetter wet seasons and drier dry seasons. Endo *et al* (2009) used data collected at more than 200 stations across Southeast Asia to examine trends in extreme precipitation indices during the period 1950–2000. They determined that, despite a decreasing trend in the numbers of wet days, average wet-day precipitation intensity in Thailand increased. Sharma and Babel (2014) also found an increasing trend in the maximum numbers of consecutive dry days (precipitation < 1 mm d^{-1}) over western Thailand. In a report covering the Indochina Peninsula, including Thailand, Villafuerte and Matsumoto (2014) and Cheong *et al* (2018) used gauge-based gridded precipitation data in Southeast Asia during the period 1911–2010 to demonstrate significant increases in annual and seasonal maximum daily precipitation ($R \times 1$ d). Exceptionally, Lacombe *et al* (2013) showed increases in the intensity and frequency of dry-season precipitation in the Mun

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[27] www.tmd.go.th/en/climate.php
[28] www.aws-observation.tmd.go.th/web/main/index.asp

River basin in northeastern Thailand over the period of 1953–2004 (i.e. a trend of the dry season getting wetter).

In addition to the amount of precipitation, rainy season characteristics such as onset and withdrawal are important meteorological parameters in Thailand. Kajikawa and Wang (2012) and Kajikawa *et al* (2012) showed an advance in the onset of the rainy season during the past three decades.

3.3. Projected changes

3.3.1. Data availability
Projections for both surface air temperature and precipitation in a warmer world are available from the Coupled Model Intercomparison Project Phase 5 (CMIP5) data archive[29], which collects the results of the latest global climate models (GCMs). Although useful, the spatial details of the GCMs are limited, as their resolution is typically coarser than 100 km (see table 9.A.1 in Flato *et al* 2013). Efforts to obtain climate projections at finer spatial scales have included the application of regional climate models (RCMs) for Thailand and its surrounding regions. Perhaps the most important of those efforts is the Southeast Asia Regional Climate Downscaling/Coordinated Regional Climate Downscaling Experiment-Southeast Asia (SEACLID/CORDEX-SEA) Project[30], a regional initiative to conduct high-resolution coordinated climate downscaling within countries in Southeast Asia. Under this framework, Cruz and Sasaki (2017) examined the performance of the Meteorological Research Institute (MRI) Non-Hydrostatic RCM of Southeast Asia for the present climate at 25 km resolution. The model represented topographic effects on rainfall well, reduced the overestimated rainfall and cold bias seen in a GCM, but underestimated the number of wet days. The datasets are not available to the public since the project is still under development.

3.3.2. Changes in temperature and precipitation projected by global models
Figure 3 shows the results of our GCM-based climate projection for Thailand, which is based on the CMIP5 climate projections of the nine GCMs analyzed in Watanabe *et al* (2014): CNRM-CM5, CSIRO-Mk3.6.0, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5, MRI-CGCM3, BCC-CSM1.1 M, and INM-CM4. Figures 3(a)and (b) show the projected trends in the annual national average (land only) air temperatures and precipitation amounts during the 21st century, modeled under the strong warming scenario outlined by the Representative Concentration Pathway (RCP) 8.5. For most of the GCMs tested, both air temperatures and precipitation show apparent increasing trends. According to the

ensemble mean of the nine GCMs, the national average air temperature at baseline (1980–1999) was 25.2 °C and that in the future (2080–2099) is projected to be 28.6 °C. Over the same period, the national average precipitation is projected to rise from 1819 mm yr^{-1} to 2046 mm yr^{-1} (figure 3(b)), a 13% increase. The projections vary considerably among GCMs, with CSIRO-Mk3.6 indicating a large increase in precipitation and IPSL-CM5A-LR predicting a decrease. The spatial distributions of the model ensemble mean changes in temperature (figure 3(c)) indicate a larger increase (>4 °C) in northern inland regions and a smaller increase (<3.5 °C) in southern coastal regions. A similar trend was determined for the change in precipitation (figure 3(d)).

Since the Asian summer monsoon is a crucial factor in determinations of warming impacts and adaptation in Thailand, several studies have examined the effects of warming on the monsoon. The IPCC AR5 report noted that the contrast between wet and dry seasons and in precipitation extremes related to the Asian monsoon would 'very likely' increase (Collins *et al* 2013). Kitoh *et al* (2013) examined the monsoonal rainfall as outlined in the CMIP5 results and found that the results showed an increase, particularly in the number of heavy precipitation events. In addition, delays in monsoon retreat dates were expected, whereas onset dates would either advance or not change. However, projections of precipitation are highly uncertain because of the large range in precipitation and temperature values among GCMs for Southeast Asia, which affects the reproducibility of the models (figure 9.38 of Flato *et al* 2013).

3.3.3. Projected changes in temperature and precipitation by RCMs
Attempts at downscaling GCM-based climate projections using RCMs have increased in recent years. One of the earliest studies to provide a future projection for Thailand using an RCM driven by a GCM was included in the IPCC's fourth assessment report (AR4). In that work, Manomaiphiboon *et al* (2013) showed increasing trends in mean temperatures and in extreme hot/warm indices, as well as intensification of heavy precipitation and dry spells, with no substantial changes in average precipitation.

SEACLID/CORDEX-SEA evaluated the performance of downscaling methods over all of Southeast Asia in accordance with selected physical factors, such as cumulus convection and surface processes, using gridded datasets (Cruz *et al* 2017, Chung *et al* 2018) and validated their results with *in-situ* observational data from selected stations (Ngo-Duc *et al* 2017). However, large variations among model projections, even when using RCMs, remain problematic, as illustrated for the Indian Peninsula (Niu *et al* 2015). In addition, the biases of GCMs are not reduced through downscaling using RCMs, as has been shown for Southeast Asia (Ngai *et al* 2017).

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[29] www.ipcc-data.org
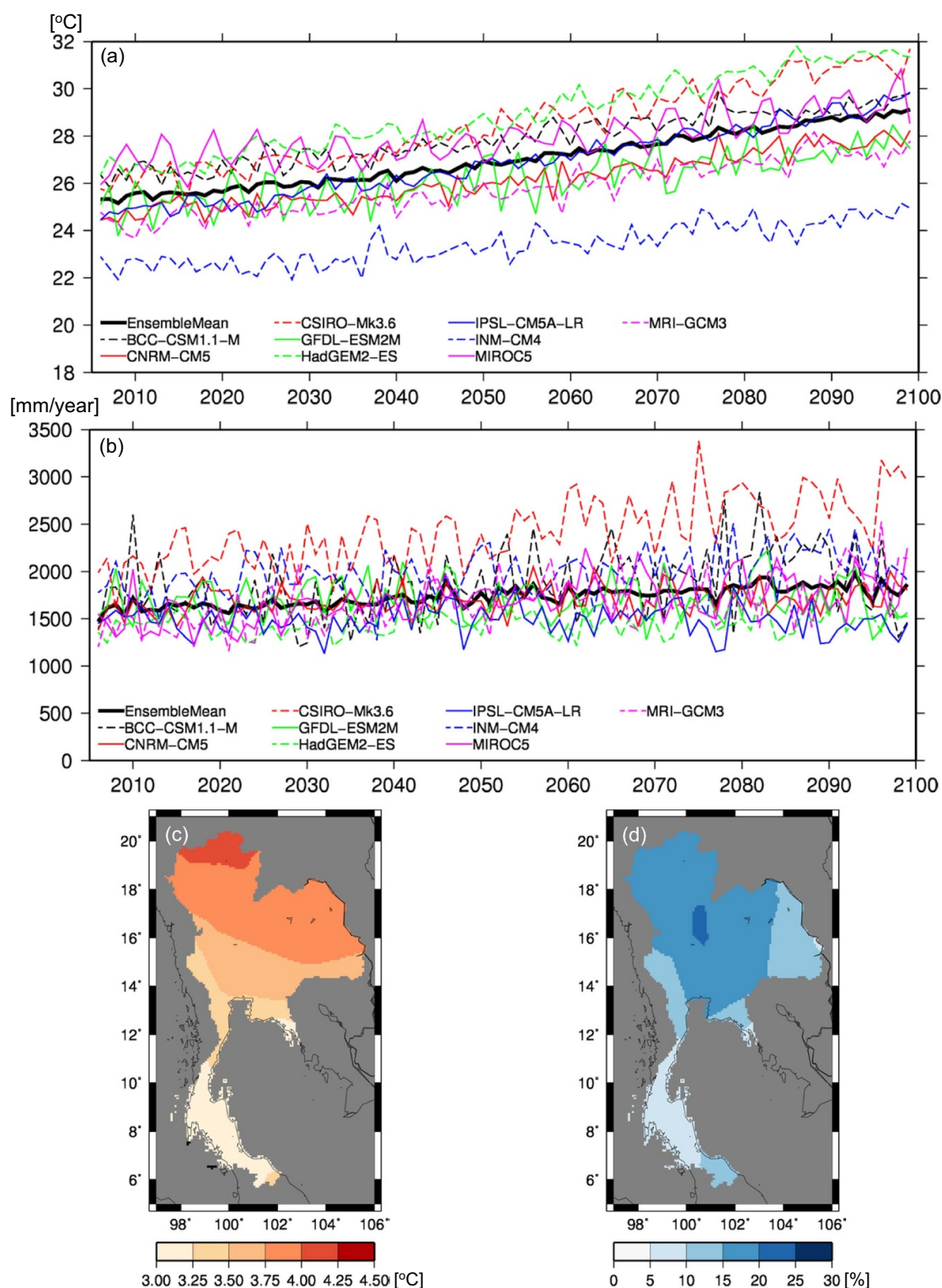[30] www.ukm.my/seaclid-cordex/

Figure 3. Future climate change projections for Thailand. The CMIP5 climate projections of nine global climate models (GCMs) under the RCP8.5 scenario: CNRM-CM5, CSIRO-Mk3.6.0, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5, MRI-CGCM3, BCC-CSM1.1 M, INM-CM4. (a) Time series of nationally averaged annual temperature. (b) Time series of nationally averaged annual precipitation. (c) Distribution of the change in annual temperature relative to the baseline period (1980–1999). (d) Distribution of the change rate in annual precipitation relative to the baseline period.

3.4. Section synopsis and discussion

Historical analyses covering past decades have generally shown increases in temperature, decreases in annual precipitation, increases in the numbers of dry days, and increases in precipitation intensity.

However, those studies were conducted using a limited amount of data. A detailed examination of the same parameters in Thailand using a larger volume of data, similar to the study conducted by Supari *et al* (2017) in Indonesia, is therefore needed. Moreover,

investigations of seasonality, such as the onset and withdrawal of the monsoon, are limited despite the importance of this information for many aspects of climate-impact analyses and adaptation measures.

Global future climate projections have shown annual temperature increases of a few degrees and an increase in annual precipitation of about 10%–20%. In Thailand, extreme events are expected to occur more frequently in the late 21st century (Kitoh *et al* 2013). However, regional variations could not be represented due to the coarse spatial resolution of the GCMs. A regional projection at high resolution downscaled by an RCM would be of value but is still under development.

In Thailand, heavy rainfall is a critical meteorological issue because it triggers flood disasters. Global warming is expected to lead to intensification of heavy rainfall over Thailand, such that improved forecasting capability is an important goal. Nguyen-Le and Yamada (2019) used a weather-pattern recognition technique to classify and then predict summertime heavy rainfall occurrence over the upper Nan River basin, in northwestern Thailand. This approach outperformed the global forecast model and can thus fundamentally improve current understanding of the genesis of heavy rainfall, the root cause of floods.

4. Sector-wise analyses

4.1. Riverine hydrology
4.1.1. Introduction
Climate change alters the magnitude, timing, frequency, and duration of precipitation as well as other meteorological variables that contribute to changes in river discharge. River discharge, including its magnitude and timing, is also strongly influenced by human activities, including land-use type, dam operation, and water abstraction. In this subsection, we focus on historical and predicted changes in river discharge.

4.1.2. Historical analysis
4.1.2.1. Data availability
River discharge in Thailand has been monitored by the RID, DWR, and the Hydro Informatics Institute (HII; known as the Hydro and Agro Informatics Institute until early 2019). Water levels are monitored at 558 river gauging stations operated by the RID and the data are converted into river discharge amounts using a site-specific flow rating curve developed for 411 stations (Royal Irrigation Department of Thailand 2018). The first river gauging station was established in 1921, at Chiang Mai on the Ping River. Many of the major river gauging stations were established in the 1950s; hence, data are available for a period of >60 years. Recent river discharge values are published in printed annual hydrology yearbooks, which are distributed to a limited number of libraries. The latest daily data are publicly available from the website

of the RID for selected stations[31]. Data on the most recent water levels of the main channel of the Mekong River, flowing along the northeastern national border of Thailand, are provided by the Mekong River Commission[32].

4.1.2.2. Observed changes
An official analysis of the long-term changes and trends in hydrology across the entire nation has yet to be published by the RID, and research in this area has been limited by the lack of availability of long-term data. However, Tebakari *et al* (2012) were able to analyze the long-term discharge of the Chao Phraya River. They reported a statistically significant change in minimum and maximum streamflows before and after the construction of two major dams, the Bhumibol and Sirikit dams, but did not detect climate-change-related alterations or new trends in river discharge. Lim *et al* (2012) analyzed the river discharge record of the upper Ping River over a period of 89 years, beginning in 1921. They found decreasing trends in the minimum and annual mean flows. Tebakari *et al* (2018) also studied the change in the flow duration curve of the Nan River as documented over 42 years and found an increase in low flow. However, the change in total precipitation was not statistically significant, which led the authors to attribute the increased low flow to land-use changes during the period investigated.

4.1.2.3. Non-climatic drivers
Land-use, reservoir operation, and water withdrawal, particularly for irrigation, are the major socioeconomic factors influencing riverine hydrology. The focus of this section is reservoir operation. Land-use changes and irrigation are discussed in detail in the sections on forest hydrology (section 4.4) and agricultural hydrology (section 4.5), respectively.

The country's dams considerably influence the hydrology in Thailand. The GRanD database (Lehner *et al* 2011), one of the most comprehensive global dam databases, lists 32 dams in Thailand, 12 of which have a storage capacity in excess of 1 km^3. The main purpose of the largest dams in Thailand is to supply irrigation water. Carry-over of the flow in the wet season to the dry season not only benefits agricultural production but also provides flood protection in vulnerable areas. For instance, during the record-breaking flood event in 2011, the two major dams in the Chao Phraya River, namely, the Bhumibol and the Sirikit dams, stored 10 km^3 of water or two-thirds of the estimated total flood discharge, which greatly reduced flood damage (Komori *et al* 2012). Despite the benefits of dams in terms of basin-wise water management, the construction of new dams in Thailand remains a matter of intense debate, due to

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[31] http://hydro-1.rid.go.th/

[32] http://portal.mrcmekong.org/river-monitoring

their other, potentially negative effects (Sneddon and Fox 2008, Kirchherr 2018).

4.1.2.4. Detection and attribution

Detection and attribution refer to the statistical identification of a change in climate or hydrology and the quantification of the contribution of a specific factor to that change (Bindoff *et al* 2013). Detection and attribution studies are typically conducted by applying long-term statistical analyses and climate simulations. However, detection of changes in river discharge is challenging because of internal (i.e. inter-annual) variability, and only a few studies have succeeded in detecting streamflow changes at the basin or national scale (Mondal and Mujumdar 2012, Sarojini *et al* 2016). To our knowledge, there has been no formal detection and attribution study of Thailand or the Indochina Peninsula. Peterson *et al* (2012) conducted a long-term precipitation analysis using a global precipitation dataset and concluded that the precipitation in 2011, while causing a destructive flood disaster along the Chao Phraya River, was not a statistically rare event.

4.1.3. Future projections
4.1.3.1. Projected changes

Quantitative river discharge projections under climate change were reported in 14 of the papers identified in our literature search. Supplementary table S1 summarizes the climate scenarios, models, and key results. For the climate scenarios, most studies directly used climate projections from GCMs after applying simple spatial interpolation methods. The typical spatial resolution of GCMs is several 100 km, with the exceptions of the MRI Atmospheric General Circulation Model (AGCM) 3.1S and 3.2S (Mizuta *et al* 2012), which have resolutions of approximately 20 km. Although RCMs have been used to obtain climate projections (section 3.2.3), according to our search of peer-reviewed publications they have not been used in climate-change impact studies of riverine hydrology.

Because the hydrological response is strongly influenced by precipitation, projected hydrological changes depend on the climate scenario adopted. Three groups of studies were identified according to the employed climate scenario. Studies in the first group used multiple CMIP5 GCMs. Kotsuki *et al* (2014) estimated that the mean annual river discharge at Nakhon Sawan on the Chao Phraya River would increase substantially during the middle and late 21st century (33.7%–45.7% and 23.6%–92.2%, respectively). Similar results were reported by Watanabe *et al* (2014) (figure 4(a)). In the second group of studies, MRI AGCM3.2 S was used under RCP8.5, and moderate increases were predicted for the middle and late 21st century (0.48%–10.9% and 18.4%–19.1%, respectively; Kure and Tebakari 2012). Similar results

were reported by Wichakul *et al* (2015), Champathong *et al* (2013), Hunukumbura and Tachikawa (2012), and Ruangrassamee *et al* (2015). Finally, studies of the third group made use of ECHAM4 GCM and estimated a decrease or gentle increase in river discharge (Sharma and Babel 2013, Ponpang-Nga and Techamahasaranont 2016). Although the change in future mean river discharge varied depending on the adopted GCM, all of the studies consistently estimated an increase in high flows and a decrease in low flows under a warmer climate.

Sharma and Babel (2013) used statistically downscaled precipitation data to examine the impacts of climate change on water resources in the upper Ping River basin in Thailand and investigated the impacts of a shift in the seasonal streamflow pattern. Peak flows in future periods were projected to occur from October to November rather than in September, as observed in the base period. A significant increase in streamflow was predicted for April due to early monsoon onset, but an overall decrease during the rainy season (May to October), and an increase during the dry season (November to April) for the three future periods studied (2025, 2050, and 2095).

4.1.3.2. Significance of non-climatic drivers

To our knowledge, no studies have investigated the ability of dams to regulate flow under a changing climate in Thailand. To quantitatively analyze such effects, a good hydrological model that accounts for the effects of human management must be developed. Most available hydrological projection studies exclude the effects of human management due to limited data availability. Apichitchat and Jung (2015) conducted a 'what-if' study of dam construction. They analyzed the potential hydrological influence of the Kaeng Suea Ten dam, construction of which is planned for the upstream area of the Yom River. The authors reported that the dam would result in a moderate decrease in peak discharge during the rainy season.

4.1.3.3. Economic assessments and adaptation measures

Most previous studies have provided only projections of changes in hydrological variables due to climate change; few have assessed likely economic damage or explicit adaptation measures. In their economic assessment, Chuenchum *et al* (2017) combined the Integrated Flood Analysis System rainfall-runoff model and a regional input–output model for the Nan River to estimate direct and indirect economic losses due to a water deficit between the years 2040 and 2059. They demonstrated that with higher economic growth rates, both the water deficit and value of water tend to increase, which eventually enhances the direct economic losses. They also showed that indirect losses were two to three times larger than direct losses.

Economic assessments of the impacts of flooding enhanced by climate change are challenging, if not impossible, but analyses of past flood events may yield useful insights. The gross domestic product (GDP) in the fourth quarter of 2011 dropped by 9.0%, compared to a 3.7% rise in the third quarter. The decrease was due to a large fall in output from non-agricultural sectors as a result of flooding (Office of the National Economic and Social Development Board 2012). Tanoue *et al* (2018) used a global river and inundation model and a general equilibrium model to investigate the GDP loss due to the 2011 flood. They estimated an opportunity loss (i.e. indirect economic damage) of $8.4 billion USD, which was equivalent to the loss of assets (i.e. direct economic damage).

4.1.4. Section synopsis and discussion

In historical analyses of streamflow in the scientific literature, clear changes in streamflow have rarely been reported for rivers in Thailand. Some studies have suggested that basin development (e.g. land-use changes, dam construction) may have a strong effect on streamflow. The sign and magnitude of future changes in streamflow are inconsistent among studies. The sign of the change in mean annual streamflow is highly dependent on the GCM used. The majority of studies have predicted future increases in peak streamflow, and thus increased risk of flooding in the Chao Phraya River basin. One study using the ECHAM4/OPYC GCM showed an apparent decrease in future streamflow, accompanied by a decrease in peak flow. The key gaps in current scientific knowledge are as follows.

While the RID publishes their latest hydrometeorological data, including flood and drought risk information, they do not release long-term historical records via the Internet (however, some regional hydrological centers have recently begun to provide long-term rainfall and streamflow data). In some countries, long-term hydrological data are easily accessible online, for example, the water information system in Japan[33] and the National River Flow Archive in the UK[34]. The operational agencies in Thailand have accumulated reliable hydrometeorological observations for decades; their online release would allow detailed detection and attribution studies.

The availability of spatially detailed climate projections is also limited in Thailand, whereas in other countries detailed climate scenarios derived from RCMs are accessible, for example, the Global Warming Projection Information provided by the Japan Meteorological Agency[35] and UKCP09 provided by the United Kingdom Climate Projection[36]. Detailed

spatiotemporal climate projections that cover a period sufficient for effective climate impact assessments require a huge amount of computational resources, skills in modeling and simulation, and numerous techniques for efficient application in climate impact studies (e.g. bias correction). Effective support and technology transfer in Thailand would accelerate the progress of climate-impact studies.

The models used for climate-change impact assessments include global (or generic) land surface models such as H08 (Hanasaki *et al* 2018) and SiBUC (Tanaka 2005), internationally recognized hydrological models such as SWAT (Arnold *et al* 2012) and HEC–HMS (US Army Corps of Engineers 2001), among others. However, these models do not accurately simulate floodplain flows; therefore, most studies in Thailand have targeted the upper Chao Phraya River basin (i.e. upstream of where the river flows into the delta). In studies that have used hydrological models to estimate floodplain flows (Mateo *et al* 2014, Sayama *et al* 2015), climate-change impacts were not considered. Recently Ruangrassamee *et al* (2015) and Arunyanart *et al* (2017) applied flood inundation models in their study of climate-change impacts on the Yom and Chi rivers, respectively. Given the likely increased potential for floods in coming years and the threat to local populations, these latest modeling techniques should be employed to better estimate the risk.

The restriction of climate-change impact assessments in Thailand based on hydrological variables to the upper Chao Phraya River basin reflects the fact that it is the site of several major international research projects. While a few modeling studies of the Mun River's tributaries have been conducted (e.g. Chacuttrikul *et al* 2018), the remaining basins have been ignored.

4.2. Sediment erosion

4.2.1. Introduction

In northern and southern Thailand, heavy rainfall frequently induces sediment disasters in mountainous regions, such as slope failures and collapses. As discussed in this section, these and similar events will become more common as rainfall intensity increases due to climate change. We mainly focus on the occurrence of slope failures and collapses.

4.2.2. Historical analysis

Slope failures and collapses in Thailand are monitored by the Department of Disaster Prevention and Mitigation, which provides long-term publicly accessible records. In addition, the Department of Mineral Resources stores historical data on large landslide events in Thailand, with data available from 1988 to 2012. Because the areal coverage of these datasets is limited, the Geotechnical Engineering Research and Development Center at Kasetsart University has developed a landslide database for Thailand that uses

33 www1.river.go.jp/

34 https://nrfa.ceh.acuk/

35 www.data.jma.go.jp/cpdinfo/GWP/index.html

36 http://ukclimateprojections.metoffice.gov.uk

information on landslide events from 1970 to the present (Soralump 2010a).

Despite the many landslide and slope-failure disasters in Thailand, only a few peer-reviewed papers have focused on their long-term trends in the country. Wantanee Watanasurakit (2015) evaluated landslides and mud flows in Thailand between 1988 and 2014. The results showed that between 1999 and 2012 there were more than 54 landslide events and that their frequency was increasing. Rangsiwanichpong *et al* (2017) analyzed the trends of landslide probability and sediment transport in Thailand. They found that sediment transport in central Thailand is significantly related to the probability of landslides in the northern part of the country. Thus, landslide analysis is a key aspect of sediment management in Thailand.

Our literature search identified numerous studies investigating areas at risk of slope failure and collapse in Thailand using a combination of geographic information system (GIS) data, field surveys, and modeling techniques (Miyagi *et al* 2004, Yumuang 2006, Jotisankasa and Vathananukij 2008, Soralump 2010b, Ono *et al* 2014, Inruang and Phimonphin 2015, Khiaosalap and Tongdenok 2015, Tonnayopas *et al* 2016, Pomthong and Asavasuthirakul 2017, Rangsiwanichpong *et al* 2017), but none of these studies investigated the effects of climate change.

4.2.3. Future projections
Several studies have used GCMs to conduct numerical simulations to predict future conditions. Komori *et al* (2018) used ten GCMs and two RCP scenarios to obtain a future projection of the spatial distribution of the landslide hazard for Thailand. The frequency of a once in 100 years return period landslide was predicted to increase by more than 90% in 40% and 80% of the area of Thailand under RCP4.5 and RCP8.5 (figure 4(b)), respectively. Future hazards at the national and entire-province scales have also been investigated (Inoue *et al* 2014, Protong *et al* 2018). Land use also plays a crucial role in determining landslide risk. Trisurat *et al* (2016) set up three future land-use scenarios (trend, development, and conservation) and three rainfall scenarios (average, climate change, and extremely wet) for the Thadee watershed in southern Thailand and projected future soil loss. The results indicated that total annual soil loss for the entire watershed under conditions of a 'land use development scenario' and an 'extremely wet rainfall scenario' would generate a gross soil loss of more than twice the baseline (2009). The most notable effects of a change in land use derived from a land-use development scenario consisting of the large-scale expansion of rubber plantations.

4.2.4. Section synopsis and discussion
Previous studies indicated that rates of slope failure and collapse are increasing, and will likely be further exacerbated in upstream areas with climate change, mainly due to more frequent and intensive heavy rainfall events. The risks may be increased still further by land-use changes. Landslides produce massive volumes of sediment, which cause additional problems in downstream areas.

Residents of Thailand are adopting technologies for disaster prevention; for example, early warning systems have been established due to the more frequent sediment disasters. The landslide warning system developed by Mairaing and Thaiyuenwong (2010) relies on rainfall and soil suction measurements. Soralump (2010a) introduced a landslide warning system based on stability analysis, which made use of data gathered during detailed field investigations of soil properties and a suitably scaled topographic map. Another approach is slope reinforcement. Fowze *et al* (2012) introduced a variety of countermeasures to prevent landslides, including the use of polyester polymer geogrids to cover the surface of a slope. The central government should expand these experiments and invest in adaptation methods for areas identified as high risk in many studies.

Attention should also be paid to the many aspects of landslides and the perception of landslide events by local inhabitants. Rangsiwanichpong *et al* (2019) pointed out that some of the sediments are used as construction materials. Manandhar *et al* (2015) interviewed villagers in northern Thailand and found that they were unaware of the increased threat of landslides and the associated potential risks, simply because in recent years they have not directly experienced any landslide events. These aspects should be considered in government determinations of optimal climate-related hazard management at the local level in Thailand.

4.3. Coastal erosion
4.3.1. Introduction
Thailand's long coastline includes beaches that provide invaluable habitats for marine organisms but also support a large tourism industry. Thus, sea-level rise caused by climate change will enhance coastal erosion, with environmental and economic consequences. In this subsection, we mainly focus on shoreline changes related to sea-level rise.

4.3.2. Historical analysis
4.3.2.1. Data availability
Historical shoreline changes over the past two decades in Thailand have been monitored mainly from field observations and satellite images (Nutalaya 1996, Department of Marine and Coastal Resources 2018) covering the majority of Thailand's coastline. The results of those analyses revealed erosion of the shoreline.
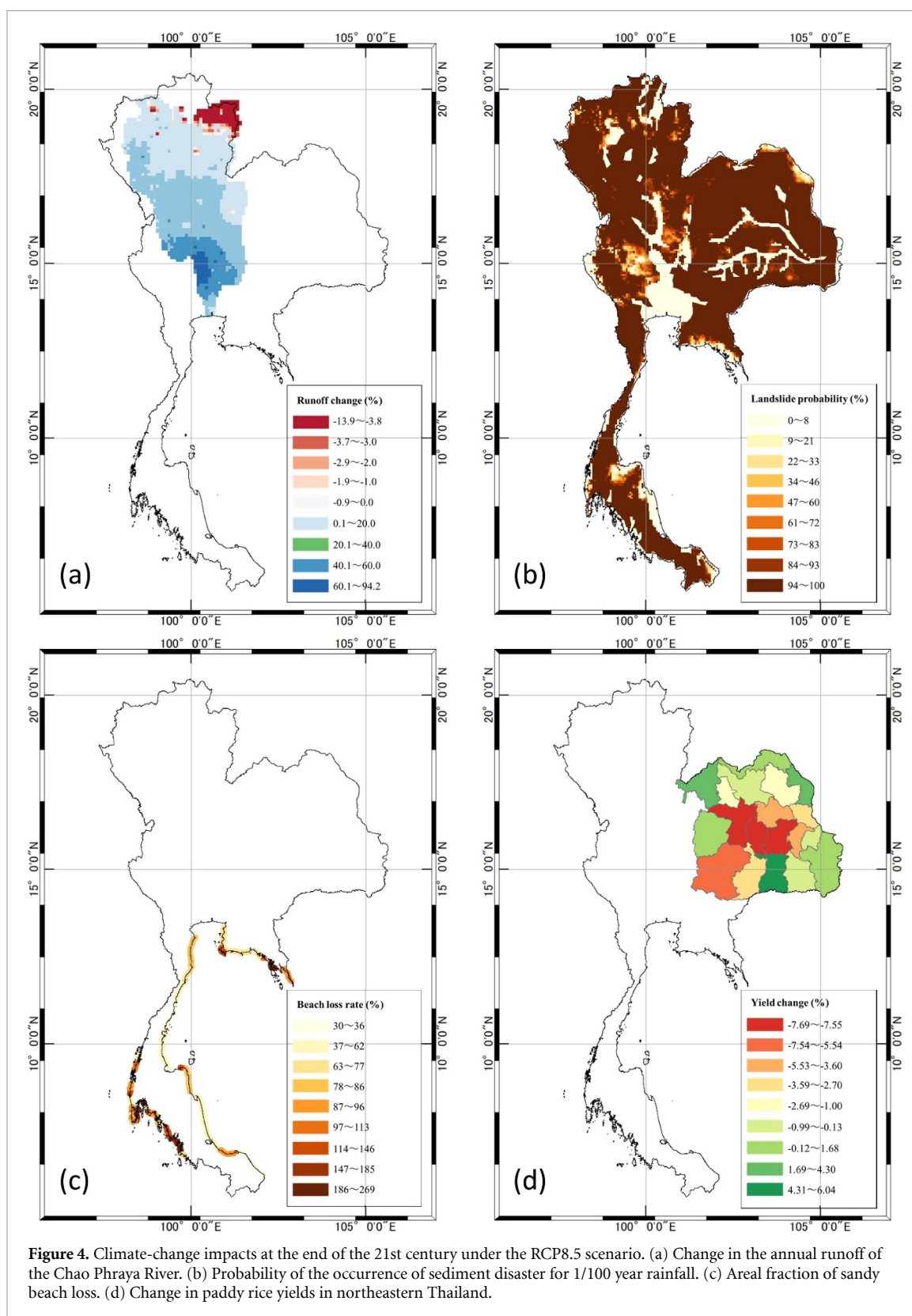
Figure 4. Climate-change impacts at the end of the 21st century under the RCP8.5 scenario. (a) Change in the annual runoff of the Chao Phraya River. (b) Probability of the occurrence of sediment disaster for 1/100 year rainfall. (c) Areal fraction of sandy beach loss. (d) Change in paddy rice yields in northeastern Thailand.

4.3.2.2. Observed trends

The erosion of muddy coasts and sandy beaches along the entire coastline during this and the previous century has been examined. From the mid-to-late 19th century, the shoreline shifted landward by 10–100 m at sandy beaches in the southern (e.g. Prachuap Khiri Khan Province, Nakorn Sri Thammarat Province) and eastern (e.g. Chon Buri Province, Rayong Province) Gulf of Thailand (Nutalaya 1996, Saengsupavanich *et al* 2009). Erosion was even more severe in the delta areas, with the muddy coast of the Chao Phraya River delta retreating by 1 km over a 40 year period (Uehara *et al* 2010). A more recent analysis of a series of aerial photographs taken by the

Department of Coastal and Marine Resources showed that about 23% of the entire coastline had eroded over the past 10 years (Department of Marine and Coastal Resources 2018).

Several studies have investigated relative sea-level rise (RSLR) using tide gauge data obtained along Thailand's coastlines over the past decade based on records covering at least 15 years (e.g. Trisirisatayawong *et al* 2011, Saramul and Ezer 2014). Those studies showed extreme spatial variations of RSLR among regions, with rates of ~1–20 mm yr^{-1}. The highest rate of sea-level rise was found in the upper Gulf of Thailand due to land subsidence induced by groundwater extraction. In addition, a significant increase in RSLR across the entire region was detected after the 2004 Sumatra–Andaman Earthquake and Indian Ocean tsunami, at a rate of ~19–34 mm yr^{-1} (Saramul and Ezer 2014). Such RSLR acceleration is associated with land motion along the Thailand coast, and is greater than the mean increases indicated by global tide gauges (~1.7 mm yr^{-1}) (Church and White 2011).

Regarding coastal storms, the Thailand Metrological Department (TMD) has recorded the numbers of tropical cyclones impacting Thailand each year during the period 1951–2019. They reported an increase in frequency, with 12 tropical cyclones and 1 typhoon recorded during the past three decades, including major storms such as Typhoon Gay (1989), Tropical Storm Linda (1997), and Tropical Storm Pabuk (2019) (Thai Meteorological Department 2020). There have been no reports of shoreline recession caused by coastal storms in Thailand due to a lack of available historical shoreline data. However, Williams *et al* (2016) proposed that there is a connection between global warming and the increasing number of intense typhoons reaching Thailand, based on geological evidence from prehistoric typhoon strikes.

4.3.2.3. Non-climatic drivers

In our literature survey, the impacts of coastal erosion were attributed to natural phenomena and to anthropogenic activities, but the dominant factors differed among regions. For example, in addition to storm surges, ports and coastal protection structures contribute to the shoreline retreat of sandy beaches in eastern and southern Thailand (Saengsupavanich *et al* 2008, 2009). The muddy coasts occupied by mangrove forests in the eastern and western Gulf of Thailand are damaged by the strong waves that occur during the monsoon season, which together with dam construction in rivers has depleted the sediment supply (Nutalaya 1996, Thampanya *et al* 2006, Saengsupavanich 2013). In addition, the RSLR caused by rapid land subsidence due to groundwater pumping and sediment depletion has negatively affected the Chao Phraya River delta (Nutalaya 1996, Uehara *et al* 2010, Saramul and Ezer 2014).

4.3.2.4. Socioeconomic impacts

The losses associated with coastal erosion are both physical and financial. Several reports described building and coastal infrastructure damage (Department of Marine and Coastal Resources 2018). In Nakhorn Sri Thammarat Province, the rising sea level has forced 10–20 local people to evacuate and abandon their houses every year. Further losses for the local community can be expected, such as the loss of shrimp farming revenue due to shrimp pond erosion (Saengsupavanich *et al* 2009).

4.3.3. Future projections
4.3.3.1. Projected changes

According to IPCC AR5 (Church *et al* 2013), by the end of the 21st century, sea-level rise is expected to affect almost all coastlines worldwide, including those in Thailand. To predict erosion, many studies have used the Bruun (1962) rule due to its simplicity (Hinkel *et al* 2013) and lack of a requirement for data on sediment particle size, beach profile, beach slope and oceanographic factors (i.e. waves and tides). Such studies have focused on the Black Sea (Allenbach *et al* 2015); Florida, USA (Dean and Houston 2016); and Japan (Udo and Takeda 2017). In contrast , the process-based model developed by Ranasinghe *et al* (2012) and applied to Sydney, Australia, goes beyond the Bruun rule.

The regional ensemble-mean sea-level rise in Thailand projected by the IPCC ranges between 0.34 and 0.65 m, which would cause inundation of low-lying areas and recession of erodible shorelines (section 13.6.5 of Church *et al* 2013). Notably, CMIP5 did not consider projections related to the Antarctic ice sheets (Horton *et al* 2014, U.S. Global Change Research Program 2017), which may contribute to more than a meter of sea-level rise by the end of 2100 (Deconto and Pollard 2016). The future impacts of sea-level rise on inundated populations and mangrove areas have been described (Barbier 2015). The Department of Marine and Coastal Resources uses tide gauges to collect tide data, and wave data are available from the Geo-Informatics and Space and Technology Development Agency; satellite altimetric observations are also freely available. Ritphring *et al* (2018) collected data on sediment size and beach slope through field measurements performed across Thailand in 2010–2017. Based on the four RCP scenarios, shorelines were projected to retreat by 46%–72% (25–40 km^2) of the total sandy beach area (figure 4(c)).

4.3.3.2. Significance of non-climatic drivers

Vongvisessomjai (2010) examined the relationship between river sedimentation and coastal erosion and attributed the latter mainly to a decrease in the amounts of sediment supplied from rivers to the sea. However, the relationship between sediment disasters and climate change has not been well studied.

4.3.3.3. Economic assessments and adaptation measures

Many coastal cities in Southeast Asia, including Bangkok, exposed to sea-level rise face economic difficulties due to rapid population growth in low-lying areas (Uehara *et al* 2010, Dasgupta *et al* 2011). In Thailand, the socioeconomic impacts of sea-level rise are likely to be significant. Barbier (2015) found that a 1 m sea-level rise could cause Thailand to lose up to 31.6% of its coastal GDP (6% of national GDP) if no adaptations are made. Among the limited number of economic impact assessments of coastal erosion in Thailand, most have been conducted at the local or regional scale. For example, Kulpraneet (2013) evaluated the potential effects of sea-level rise on fishing villages in the upper Gulf of Thailand over the next 30 years. They estimated that the cost of adaptation measures for individual households could reach 340 000 Thai Baht. Moreover, sandy beaches are important resources in Thailand, and their erosion will likely cause a decrease in tourism revenue, as observed in other countries (Ng and Mendelsohn 2006, Alexandrakis *et al* 2015).

4.3.4. Section synopsis and discussion

Whether past coastal erosion in Thailand was driven by climate factors is unclear, but according to the projected results of Ritphring *et al* (2018), climate change will lead to significant losses of sandy beaches. Given the rapid development of Thailand's coastal zones, there is an urgent need for countermeasures to deal with future sea-level rises. For project planners, cost–benefit analyses could be used as a tool to determine the necessary adaptations. Economic assessments of coastal erosion are both a prerequisite for these analyses and essential for long-term adaptation planning in Thailand.

4.4. Forest hydrology

4.4.1. Introduction

Forests account for 35% of the land cover in Thailand (Food and Agriculture Organization 2015). Since the second half of the 20th century, Thailand has experienced drastic deforestation. Forests are now predominantly distributed in mountainous regions, where hydrometeorological conditions differ from those of the plains. In this subsection, we focus on rainfall and streamflow in forests and mountainous forest-covered upstream watersheds, as these areas are monitored differently than downstream plains. We also investigate the effects of land-use changes, as deforestation is ongoing in some regions.

4.4.2. Historical analysis

4.4.2.1. Data availability

Rainfall is the key element to understanding forest hydrology. However, the hydrometeorological observation network in Thailand's mountainous forest region is insufficient (Kuraji *et al* 2009). While the TMD has rainfall stations throughout Thailand, most are located in towns. The RID and HII also operate rainfall stations, but the majority are located along or near rivers. The deficient coverage has hindered the collection of detailed spatial rainfall information in forest watersheds. Only the Department of National Parks (DNP) has a small number of rainfall observation sites in some national parks in the mountainous regions of Thailand.

4.4.2.2. Observed changes

The impact of climate change on rainfall in mountainous regions of Thailand is poorly understood. Endo *et al* (2009) analyzed the trend in heavy rainfall in Southeast Asia and found significant increases and decreases of extreme rainfall in the northern mountainous region and on the eastern flank of the Arakan Mountains of Myanmar, respectively. However, there have been few studies of the rainfall trends in the mountainous areas of Thailand, due to the above-mentioned lack of data from these regions. Using 10 year intensive observation data of continuous rainfall from Mt. Inthanon (the highest mountain in northern Thailand) and the Mae Chaem basin, Kuraji *et al* (2009) found an altitudinal increase in annual rainfall hours but no trend in mean rainfall intensity. Tebakari *et al* (2018) reported that there was no statistically significant trend in precipitation in the mountainous Nan River basin, a conclusion drawn from long-term observation data of the region collected over the second half of the 20th century.

Only a few studies have examined past changes in runoff in the context of climate change. Chacuttrikul *et al* (2018) examined the effects of climate and land-use changes using a hydrological model. They reported that during the 20th century, the effects of land-use changes on the Lam Chi River, a tributary of the Mun River (northeastern Thailand), exceeded those of climate change.

4.4.2.3. Non-climatic drivers

Land-use changes can strongly impact runoff, and may have a greater effect than rainfall in Thailand. Most of Thailand was originally covered with forest. At the beginning of the 20th century, plantations managed by foreign interests were constructed to produce rubber and agricultural crops, which led to extensive deforestation that was worsened by the removal of wood for use as a building material. Beginning in the 1950s, land cover and land use changed drastically, as forests were converted to cropland (Royal Forest Department 2017). Although deforestation has slowed since the 1980s, it continues in the Nan River basin in northern Thailand (Baicha 2016). In the 1990s, the target deforestation rate was reduced through legislation enacted by the central government (Blaser *et al* 2011). Nonetheless, the proportion of forest area in Thailand is still declining,

from around 63% in 1946–1947 (Food and Agriculture Organization 1948) to 43% in 1973 (Royal Forest Department 2017) and 35% in 2009 (Food and Agriculture Organization 2015). To reduce the potential for flood-related disasters, the Thai government began promoting forest conservation in the 1980s (Leblond 2014). The National Forest Policy and the 9th National Economic and Social Development Plan (NESDP) of Thailand (2002–2006) set targets of maintaining 40% of the country's land area as forest, with protected forests covering not less than 25% of whole country and the remaining 15% designated as production forests for timber and other forest products (National Economic and Social Development Board 2001).

The change in runoff due to land-use change has attracted more attention than that caused by climate change. Petchprayoon *et al* (2010) found an increasing trend in daily streamflow in the Yom River between 1990 and 2005, a period coinciding with the expansion of urban areas and loss of forest areas. Tebakari *et al* (2018) examined the impacts of forest cover on streamflow by analyzing historical changes in flow duration curves for the upper Nan River watershed in northern Thailand. Their study area included Nan Province, where the natural forest area decreased by 41.5% between 1995 and 2012, while the agricultural land area increased by 51.1% (Baicha 2016). Daily rainfall data did not show a significant increasing trend from 1974 to 2015, although low-flow and drought-flow discharges increased significantly over that period (see also section 4.1.2.2). Other studies have used hydrological models to examine the sensitivity of runoff to land-use changes under the present climatic conditions (e.g. Thanapakpawin *et al* 2007, Petchprayoon *et al* 2010, Wangpimool *et al* 2013, Kheereemangkla *et al* 2016). According to Dey and Mishra (2017), when devising adaptation strategies and policies for regional water resource planning and management, the impacts of climate change on streamflow must be separated from those of other human activities. Various approaches are available for achieving this separation. Land-use changes may also have altered the rainfall pattern in Thailand. Kanae *et al* (2001) considered the impacts of land-use changes on rainfall and found that large-scale deforestation over the Indochina Peninsula had caused a decrease in monthly rainfall for September.

4.4.3. Future projections
4.4.3.1. Projected changes
Our literature search failed to yield any projections of rainfall changes that explicitly considered the geographical characteristics of mountains in Thailand. Some climate change projections using RCMs include rainfall in mountainous forests; however, without ground truth data, evaluation of such projections is difficult (González-Zeas *et al* 2019).

As with runoff, several studies have investigated the impacts of both land-use and climate changes on streamflow in Thailand. For example, Amnatsan *et al* (2009) assessed the flood risk under climate change in Nan Province. Chacuttrikul *et al* (2018) reported that, in the Lam Chi River, a tributary of the Mun River, the effects of climate change would exceed those of land-use change in the 21st century, in contrast to the pattern in the late 20th century. Igarashi *et al* (2019) provided quantitative predictions of the impacts of climate and land-use changes on flood discharge by using two simulation models at a watershed in Song Khwae District, Nan Province, northern Thailand. The study had three stages: predictions of future land use (14 scenarios, each with different proportions of forest cover); calculation of 3.3 year and 10 year return period rainfall for the periods 2006–2016 and 2040–2050; and comparisons of the average daily discharge from 3.3 to 10 year return period rainfall for the 14 land-use scenarios. The results showed that, although climate change will decrease the average daily discharge from 3.3 to 10 year return period rainfalls, the discharge from future rainfall over a 10 year return period, assuming a forest area limited to <45%, will be greater than the present levels. These quantitative predictions will enable a cost–benefit analysis to be conducted, thereby contributing to efforts aimed at adaptation to climate change. Takata and Hanasaki (2020) assessed the effects of afforestation in terms of reduced flood risks and exacerbated drought risks in the upper Chao Phraya River in the context of climate change. They found a marked reduction in the amount of runoff during the wet season and an increase in evapotranspiration during the dry season, but both effects of afforestation were limited compared with the changes caused by warming. Trisurat and Arunpraparut (2019) predicted that an increase in forest cover would increase the flood volume by 3%–4% relative to the current level. Another study focused on water quality. Shrestha *et al* (2018) conducted an integrated assessment of the impacts of climate and land-use changes on hydrology and water quality in the Songkhram River, a tributary of the Chao Phraya River. The impact of climate change was shown to be greater than that of land-use changes.

4.4.3.2. Significance of non-climatic drivers
Projecting land-use changes is challenging and uncertainty may be greater than for f climate change projections. Johnson (2015) used a combination of national forest-type maps and global tree-cover maps to project natural forest loss in Thailand, estimating an increase in annual forest loss of 70.4% by 2020 relative to 2012. In Nan Province, forest cover will decrease from 61% in 2016 to 47% in 2030 if the recent trend continues. However, the rate of forest decline can be influenced by policy. Trisurat *et al* (2019) found

that in Nan Province, an ambitious target of increasing agriculture-derived income by 2% per year would allow for maintenance of 57% forest cover through 2030, with recovery to 67% if conservation measures are implemented.

4.4.3.3. Economic assessment and adaptation measures
Several studies have attempted to integrate the effects of climate, land use, and social factors. Trisurat *et al* (2016) integrated land-use and climate change scenarios into an assessment of forested watershed services in southern Thailand. They found that rainfall was more sensitive to altered water yields and soil loss than to land use, and that streamflow and nitrate loading would decrease due to the combined effects of climate and land-use changes. Shrestha *et al* (2020) evaluated land-use changes and their impact on water yields in the Songkhram River basin. They generated land-use maps up to the year 2100 on the basis of three future scenarios focused on economy, conservation, and agriculture. Under the economic scenario, an increase in water yields as a result of an increase in urban area and rubber plantations was determined, whereas under the conservation scenario a small decrease in water yields was predicted.

4.4.4. Section synopsis and discussion
Due to limited availability of hydrometeorological observations, historical trends of rainfall and runoff in forested mountain areas in Thailand are unclear. A number of studies have attributed the change in runoff to land-use changes. Few projections of future rainfall in forests have been reported, in part due to the lack of ground-truth data. In contrast, a considerable number of runoff projections were found, including projections related to land-use and climate changes. As land-use projections are themselves highly uncertain, runoff projections differ markedly.

An important challenge in forest hydrology is the lack of rainfall information for mountainous regions. Although satellite and radar observation data are available, improved accuracy awaits calibration using ground-based rainfall observations. As noted in section 4.4.2.1, ground-based rainfall observations in Thailand are unevenly distributed. To solve this problem, the DNP is planning to cooperate with the RID and TMD to install ground-based rainfall monitors in mountainous areas. The data can then be used to validate remote-sensing data, which will improve simulations of river discharge.

Although we focused on forest hydrology, the impacts of climate change on forest ecosystem are of great concern. Deb *et al* (2018) reviewed the available literature on the impact of climate change in tropical forests in Asia and identified two issues for consideration in future tropical forest research: the effect of climate change on the extinction risk of tropical trees, and the integration of climate change risks into forest policy and management.

Our literature survey showed that land use and hydrological changes have been extensively studied in Thailand. Those studies showed that while forests can mitigate small and local floods, they have no apparent influence on extreme floods or flooding at the large catchment scale (Calder *et al* 2007). Calder (2005) concluded that the benefits of forest cover are reduced as the severity of flooding increases. Notably, field studies generally indicate that forest-management activities, such as cultivation, drainage, road construction, and soil compaction during logging, are more likely to influence the flood response than is the mere presence or absence of forests. With the recent economic growth in developing countries, land use in the countryside has changed to meet increasing food exports (Lambin and Meyfroidt 2011).

4.5. Agricultural hydrology

4.5.1. Introduction
Agriculture is one of the key industries in Thailand. Total water withdrawal in Thailand in 2004 was 57.47 km^3, of which 90.4% was for agriculture (irrigation) (World Bank 2011). In 2017, Thailand was the world's sixth largest producer of paddy rice[37], which requires much larger volumes of irrigation water than other upland crops. This subsection focuses on agricultural production and water use, especially for paddy rice production.

4.5.2. Historical analysis
4.5.2.1. Data availability
General crop production data, such as planted area, harvested area, and crop yields, are partly available at the provincial level for the years 1981 until 2018 (Office of Agricultural Economics 2013). Water withdrawal for irrigation is monitored by the RID, but publicly available data are limited. Sethaputra *et al* (2001) reported the sector-wise water requirements for 25 major watersheds in Thailand.

4.5.2.2. Observed trends
Rice cultivation is subdivided into rainfed wet-season rice and irrigated dry-season rice. For wet-season rice, the average yield increased from 2.1 ton ha^{-1} in 1998 to 2.84 ton ha^{-1} in 2018 (35% increase; supplemental figure S2), which is mainly attributed to improved farming practices, such as the introduction of new varieties and application of fertilizer and irrigation water. For dry-season rice, the average yield was 4.1 ton ha^{-1} in 1998, with little change until 2018, but the total planted area increased from 1.1 million ha in 1998 to 3.0 million ha in 2012.

Because multiple factors lead to changes in crop yields, isolating the specific effects of climate change is difficult. Polthanee and Promkhambut (2014) estimated the impact of climate change on crop yields in

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[37] www.fao.org/faostat

northeast Thailand by comparing data from 1981 to 1996 and 1997 to 2012. The annual mean maximum temperature increased by 0.21 °C and the mean temperature by 0.51 °C. Due to the earlier arrival of peak monthly rainfall during the wet season by 1 to 2 months, farmers have had to adapt by planting crops earlier. The shift in the crop calendar has changed seasonal water use by the agricultural sector. Prabnakorn *et al* (2018) employed a regression model to assess how temperature changes affected rice yield using data from 1984 to 2013 in the Mun River basin. They showed that the impact on yield of increased temperature was less than -0.05 ton ha^{-1} and concluded that the increasing trends in the minimum and maximum temperatures were associated with modest yield losses relative to the average rice yield of 2.1 ton ha^{-1}. By contrast, precipitation correlated positively with yields in all months, except the wettest month (September). The planted area of rice is another important factor and varies by as much as $\pm10\%$ year by year depending on water availability. The planted area of rice correlated positively with accumulated rainfall in June and July, especially in northeast Thailand, where rainfed paddies predominate (Tanaka *et al* 2016).

Agricultural water demand has increased rapidly, from 68.2 km^3 in 2001 to 114.1 km^3 in 2018, with the latter quantity exceeding the estimated amount of potentially available water (102.0 km^3) (Sethaputra *et al* 2001, Apipattanavis *et al* 2018). This growth is mainly attributed to the increase in planted area. We were unable to find any reliable studies discussing the effects of climate change on water withdrawal. The RID has developed a number of large-, medium-, and small-scale reservoirs for irrigation and storage, increasing capacity from 24.3 km^3 in 1971 to 36.6 km^3 in 2006 (Tabucanon 2006).

4.5.2.3. Non-climatic drivers
A distinct increase in the total planted area was observed, from 9.3 million ha in 1998 to 10.8 million ha in 2012 (16% increase), followed by a gradual decrease to 9.4 million ha in 2018 (supplemental figure S2).

Water use in the agricultural sector is strongly affected by planted area. Typically, intensive use of irrigation for dry-season rice cultivation triggers water shortages in downstream areas. The price of rice is the key incentive encouraging farmers to increase planted area. Due to the steep rise in the global market price for rice in 2009, the planted area of rice in both the wet and dry seasons increased by 1 million ha through 2012 (Office of Agricultural Economics 2018).

Irrigation efficiency is another important factor in meeting irrigation water demands. Vudhivanich *et al* (2002) collected data from 25 irrigation projects in the Chao Phraya River basin and estimated an average irrigation efficiency of 39.4%

(range: 14.6%–55.4%), which was lower than that of developed countries. Improvements are therefore needed to reduce water use in the agricultural sector.

4.5.3. Future projections
4.5.3.1. Projected changes and trends
Several studies have projected changes in crop yields under climate change conditions. Most of these studies show general decreases in rice crop yields due to higher air temperature, with some exceptions. Based on the A2 climate change scenario of IPCC AR4, Babel *et al* (2011) projected a decline in rice crop yields in northeast Thailand of 18%, 28%, and 24% for the 2020s, 2050s, and 2080s, respectively, compared with the average yield during the period 1997–2006. Shrestha *et al* (2017b) studied the potential impact of climate change on rice yields in northeast Thailand and found a decrease for the rice cultivars KDML105 (Thai jasmine rice) and RD6. Projected yield decreases in the 2080s under RCP4.5 and RCP8.5 were 37% and 38% for cultivar KDML105 and 13% and 18% for cultivar RD6, respectively. The results of Chun *et al* (2016) were more pessimistic, as under the RCP 8.5 scenario they estimated a reduction in rice yields of >45% in most of Thailand by the 2080s. A 73% reduction was attributed to the increase in temperature, as daily air temperatures >35 °C damage crops, and even hotter days during the ripening stage significantly reduce rice production. Under RCP8.5 crop yields in the central provinces of northeast Thailand, where annual rainfall is lower than in other provinces, will be severely impacted (figure 4(d)). By contrast, Arunrat *et al* (2018) predicted that climate change will positively impact rice yields in Roi Et Province, northeast Thailand. Rice yields were predicted to increase significantly, by 0.7% (RCP8.5: 2060–2079) and 18.8% (RCP6.0: 2080–2099). While the authors noted that rising temperatures would reduce rice yields, they argued that the effect would be compensated by CO$_2$-mediated fertilization and increased precipitation. As a result, future projections of rice yields according to changing climatic conditions have high uncertainty. Previous studies assumed that agricultural technologies would not change in future scenarios; however, modernization of farming practices will have a greater influence on rice yields than climate change.

Several studies have projected changes in irrigation-water demands under climate change. Koontanakulvong *et al* (2013) used the A1B scenario of IPCC AR4 to evaluate future water supplies and the irrigation water demands at Sirikit dam, in Phitsanulok Province. In drought years, annual water supply was predicted to be significantly decreased compared to the period 1979–2006, by 18.3% between 2015 and 2034 and by 16.1% between 2075 and 2099. However agricultural water demands were expected to increase slightly, by 1.13% during the period 2015–2034 and 0.5% during the period 2075–2099. A temperature

rise increases crops' water requirements. Boonwichai *et al* (2018) found increasing trends in both maximum and minimum temperatures, with an expected increase of 1.9 °C by the 2080s (2070–2094) under the RCP8.5 scenario. In that same analysis, crop water requirements were expected to increase by the 2080s, by 17% under RCP4.5 and 18% under RCP8.5. Due to the increase in crop water use and the decrease in rice yields, crop water productivity by the 2080s could decrease by 32% under RCP4.5 and 29% under RCP8.5.

4.5.3.2. Significance of non-climatic drivers

Crop production is influenced not only by climate, but also by land use, biological technology, farming technology, and other factors. Iizumi *et al* (2017) estimated the global future production of wheat, rice, maize, and soybeans, accounting for nitrogen application, knowledge of agricultural technologies, irrigation intensity, and other management factors. Although obtaining plausible projections of these factors in Thailand is highly challenging, their analysis is nonetheless worthwhile because of the substantial impacts of these factors on yield projections.

Government policy is another key driver of agricultural hydrology. Over the last few years, the Thai Government has promoted a national agenda called 'Thailand 4.0', with the aim of attaining a value-based system that drives the nation's economy through innovation and technology. Agriculture is one of the five sectors focused on in the 'work less, gain more' paradigm.

4.5.3.3. Economic assessments and adaptation measures

Shifting the crop calendar is one of the most practical adaptation measures. However, Shin *et al* (2017) analyzed the response of rice yields to autonomous adaptation under the multi-model projections of CMIP5 and showed that the gains from shifting planting dates and switching rice varieties were marginal in Thailand, where the climate is already near the upper temperature limit for rice growth. Boonwichai *et al* (2019) reported that rainfall patterns are expected to shift earlier, which would require moving the planting date forward to avoid the water-deficit period. However, this would coincide with periods of high temperatures, in turn increasing crops' water requirements.

Crop calendar shifting in combination with flood or drought warnings may be effective if the warnings are accurate. Currently, farmers alter their crop calendars in response to advisories from the RID (Royal Irrigation Department of Thailand 2011). For the 2019 season, irrigation began at the beginning of November 2018, due to the nationwide drought forecasted by the RID. Since droughts proceed slowly, predictions of their adverse effects are subjective and difficult to verify. Raksapatcharawong

and Veerakachen (2018) developed a web service to evaluate the drought hazard for Thailand based on three satellite products: the normalized difference vegetation index, land surface temperature, and rainfall. Drought-related information, including intensity, duration, risk, and vulnerability, is communicated via GIS. Both farmers and the authorities can take advantage of this service to initiate adaptation measures, such as crop change or rain making, respectively.

Rice cultivation techniques based on less intensive irrigation are a crucial adaptation to the changing climate. Alternate wetting and drying (AWD) is among the water-saving techniques with the potential to reduce the requirement for irrigation water. Maneepitak *et al* (2019) tested the performance of AWD in Ayutthaya Province, central Thailand, and showed that it reduced total water input by 19% during the wet season and 39% during the dry season, resulting in an improvement in total water productivity of 46% in the wet season and 77% in the dry season.

Flood-retarding ponds (called 'monkey cheeks' because monkeys can store bananas in their cheeks) that collect flood water for use in irrigation are now located in several regions of Thailand, including the lower reaches of the Chao Phraya River. Koontanakulvong and Suthidhummajit (2015) estimated that groundwater recharge in the central Chao Phraya River basin will decrease 50% in the 2090s. A technique for enhancing groundwater storage, called managed aquifer recharge, has been studied (Pavelic *et al* 2012). The shallow groundwater at the high terrace zone of the Chao Phraya River basin can be effectively managed as a significant water supply for agricultural activities during the dry season, based on its capacity to support sustainable independent agriculture management. Thus, production can be increased while investment costs are reduced (Suanburi and Yoshida 2018).

Crop species transfer has the potential to increase farming income and reduce water demands in the agricultural sector (Polthanee 2018). In the 12th NESDB (Office of the National Economic and Social Development Board 2016), the Thai government recommended that farmers cultivate cash crops rather than rice to increase crop diversity and therefore their income. However, some upland crops are even more sensitive to weather than rice. Yoshida *et al* (2018) evaluated the weather-induced economic losses of three major crops, wet-season rice, sugarcane, and cassava, and advised avoiding a monoculture system. As an alternative, the authors recommended a mixture of sugarcane and cassava to increase farming incomes in both flood and drought years. However, most farmers tend to apply short-term measures, such as water pumping during drought, rather than long-term strategic adaptations, such as adopting

crops and crop varieties better adapted to variable climate conditions (Suwanmontri *et al* 2018). It should also be kept in mind that some of the long-term climate adaptations require changes in the farming system that are costly and labor intensive and might therefore be difficult for farmers in Thailand to implement.

4.5.4. Section synopsis and discussion

The rice crop yield in Thailand has shown steady increase in recent decades, mainly due to improvements in agricultural technology and practice. The effect of climate change has not presented an obstacle to yield growth so far. Irrigation water demand has also increased, but this can mainly be attributed to an increase in the planted area, and the effect of climate change is unclear. The majority of earlier studies show that future temperature increase leads to a decrease in crop yield and an increase in agricultural water demand. We identified a variety of papers that introduce recommended adaptations. Although the annual production in the future may be sufficient to meet domestic demand, a reduction in the rice export from Thailand may significantly affect the global market.

Further reform of agriculture for more efficient production is key to tackling this problem. For example, one major strategy is active implementation of effective farmland management that considers the entire supply chain, from resources to production (Jones and Pimdee 2017, Puncreobutr 2017). Implementation of the latest information may be also helpful. Farmers should be educated and equipped with the tools and technology necessary to make decisions (such as what, when, and where to plant) based on up-to-date information stored in intelligent cloud systems and conveniently accessed on mobile devices (e.g. the Farmer Info app, which can be downloaded for Android and iOS; www.etda.or.th/content/farmer-info.html). As a result, land use and crop water requirements are expected to become more sustainable.

4.6. Urban hydrology

4.6.1. Introduction

Increasing urbanization is a global phenomenon (Dobbs *et al* 2015). Due to the density of buildings, pavement, and heat emissions, the hydrometeorological conditions in cities differ substantially from those of the countryside. The impacts of climate change on cities, particularly higher air temperatures and intensive rainfall, are a major concern. In this sub-section, we focus on flood disasters in Bangkok, the capital of Thailand.

Bangkok is located in the deltaic plain of the Chao Phraya River basin and is one of the largest cities in Southeast Asia. Its current population is 8.3 million, which is 12% of the population of Thailand.

Beginning with the period of rapid economic growth, Bangkok's population and urban area have increased since the 1960s (World Bank 2018). Between 1986 and 2002, the residential area in Bangkok more than doubled, from 181 to 366 km^2, while the commercial area increased from 18 to 61 km^2 (Dhakal and Shrestha 2016). Both of these areas are mainly concentrated in the inner core of the city.

4.6.2. Historical analysis
4.6.2.1. Data availability

Meteorological conditions in Bangkok are monitored by the BMA and TMD. The BMA operates a total of 76 rainfall stations (51 stations for the East BMA and 25 for the West BMA). The TMD records meteorological variables including precipitation, temperature, and humidity at the Bangna Agrometeorological Station[38]. The water levels of rivers and canals are monitored by both the BMA and RID.

4.6.2.2. Observed trends

The mean annual temperature in Bangkok increased at a rate of 0.06 °C yr^{-1} between 1982 and 2010 (Klongvessa and Chotpantarat 2015). The maximum daily rainfall between decreased 1980 and 2010, except in the city core, where an urban heat island effect has been documented (Klongvessa and Chotpantarat 2015).

Floods in Bangkok can be divided into two types. River flooding from the Chao Phraya River consists of large inundation volumes and causes massive damage in Bangkok. Urban flooding is the result of severe water logging due to local intensive rainfall and is a common occurrence (Saito 2014). Bangkok suffered severe river floods in 1942, 1983, and 1995 as well as the Great Flood of 2011, which was the worst flood event in Thailand of the previous 50 years (Shrestha *et al* 2017a). In addition, severe water logging occurs frequently, due to local intensive rainfall and impermeable urban surfaces. This problem is further exacerbated by insufficient drainage capacity, garbage clogging of the drainage system, and inappropriate land use (Limthongsakul *et al* 2017). Even an ordinary amount of rain causes severe problems for some areas of the city and results in inundation for several days. The water depth in those areas may reach 20–50 cm, which creates large infrastructure problems and huge economic losses involving property and goods (Wongsa *et al* 2019). Land subsidence is another factor that increases the risk of flooding (Thanvisitthpon *et al* 2018). It has been a critical issue since 1978 and particularly through the 1980s, with the total subsidence in Bangkok by 1988 ranging from less than 20 cm to more than 160 cm (Dutta 2011).

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[38] www.aws-observation.tmd.go.th/web/reports/weather_days.asp (accessed 7 April, 2019).

4.6.3. Future projections
Several studies have estimated the impacts of future meteorological and climatic changes on flooding in Bangkok. Shrestha *et al* (2017a) studied rainfall projections for Bangkok under a warmer climate and analyzed the climate projections of nine GCMs (CNCM3, GFCM21, HADCM3, HADGEM, INCM3, IPCM4, MPEH5, NCCCSM, and NCPCM). They reported increases in the average maximum daily rainfall in Bangkok in all months during two periods (2011–2030, 2046–2065) compared to the base period of 1981–2010. The once-in-2 year (20 year) 3 h rainfall was projected to increase compared to the base period by 2.4%–27.8% (1.3%–30.4%) during the period 2011–2030 and by 5.4%–27.0% (8.5%–41.2%) during the period 2046–2065 (Shrestha *et al* 2017a). Shrestha *et al* (2015) conducted flood simulations in Sukhumvit, a district in central Bangkok, and found that, under the A2 scenario, once in 2 year and 20 year flooding will become significantly more frequent than during the base period and reach severe levels in the period 2046–2065, with increases in the pluvial flood volumes of 10.0%–11.9% and 9.8%–24.1%, respectively.

Due to its low elevation, Bangkok is vulnerable to sea-level rise. Considering the likely level of sea-level rise in Bangkok, the inundated area will be greater than that inundated by the flood event of 1995, by 26% in 2050 with a sea-level rise of 32 cm, and by 81% in 2100 with a sea-level rise of 88 cm (Dutta 2011). The population exposed to flooding in Bangkok is currently estimated to be 907 000, but is expected to increase to >5 million by 2070.

The economic losses related to infrastructure damage are currently estimated at $39 billion, but may reach a staggering $1.12 trillion by 2070 (OECD 2007). Other adverse impacts, including those on water availability, the urban heat island effect, and public health, are expected in Bangkok (Dhakal and Shrestha 2016).

4.6.4. Section synopsis and discussion
In this review, we identified studies that investigated the impacts on flooding of precipitation changes and sea-level rise in Bangkok. Their findings showed that climate change and sea-level rise will exacerbate future flood damage in Bangkok. Although insightful, those studies primarily considered climatic factors; socioeconomic changes that will drive much of the damage have not been fully considered. Integrated assessment of climatic and socioeconomic changes remains a major challenge.

The BMA prepared a climate change adaptation plan in 2015, and efforts to adapt to climate change have been made in various sectors. The BMA and Japan International Cooperation Agency compiled the 'Bangkok Master Plan on Climate Change 2013–2023' in 2015 (Bangkok Metropolitan Authority Japan International Cooperation Authority 2015).

Its adaptation measures consist of those aimed at managing flooding, coastal erosion, drought, and salinity intrusion. The measures are prioritized as short-term (1–3 years), mid-term (3–5 years), and long-term (5–10 years) actions to prevent or minimize the impacts of climate change and to construct the appropriate infrastructure. The flooding adaptation measures include expansion of retention areas and the development of a flood management information system that is linked to other sectors, such as road construction. Of interest in urban areas are climate change adaptation measures such as green infrastructure and ecosystem-based disaster risk reduction (Alves *et al* 2018). To limit coastal erosion, the construction of stone dykes and evacuation roads and the development of hazard maps are planned. Measures to control drought and saline intrusions include public awareness campaigns to encourage citizens to minimize water use and the implementation of a drought management plan as a comprehensive measure. Although promising, these measures are not always based on quantitative projections of future conditions, making it difficult to assess the feasibility and effectiveness of the proposed activities. Agencies and research institutions must develop evidence-based plans and evaluation methods.

5. Cross-sectoral analysis

In this section, the analyses in sections 3 and 4 are integrated by focusing on regionality (section 5.1) and disaster risks (section 5.2)

5.1. Regionality of the impact and adaptation studies

Published papers on climate-change impacts and adaptation in Thailand were surveyed for each of the six water sectors (excluding meteorology) reviewed herein: riverine hydrology, sediment, coastal erosion, forest hydrology, agricultural hydrology, and urban hydrology. A Web of Science search was performed using the keywords for the topics listed in table 1. Those keywords were used to search the title, abstract, authors' keywords, and 'KeyWords Plus (R).' The latter is an index term automatically generated from the titles of cited references and it means that papers targeting the global, Asian, and Southeast Asian domain were recognized as hits if they frequently cited papers on Thailand. Relevant papers for this study were selected from the search results and the study areas were identified from the titles and abstracts. The study areas of the selected papers ranged from a specific location within Thailand to the whole world. The specific locations within Thailand were divided into the five sub-regions shown in figure 1(a). A paper whose target area included more than one sub-region in Thailand was classified as 'Thailand.' Papers that included results outside Thailand were classified as 'Southeast Asia,' 'Asia,' or 'global' depending on

the study area, although some referred to a specific area within Thailand. Papers targeting Southeast Asia were distinguished from those targeting the whole of Asia because the climatic and social conditions of Southeast Asian countries are more similar to those of Thailand. The number of double-counted papers was subtracted when two searches were conducted for a single sector.

Figure 5 shows the regional fractions of the numbers of published papers for each sector. Among studies of the sub-regions of Thailand, those on riverine hydrology, sediment erosion, and forest hydrology were concentrated in northern Thailand because of its mountainous terrain and the ongoing deforestation in that region. Studies on agricultural hydrology were concentrated in northeastern Thailand because of the marked shortage of water for agriculture during the dry season. Studies on urban hydrology were concentrated in the central region, where Bangkok is located. The central region was also the focus of studies on agricultural hydrology and coastal erosion because of its vast paddy fields and the soil-erosion problems affecting the Chao Phraya delta. Very few studies targeted the eastern region, probably because of its small areal coverage. Most of the studies on sediment erosion and coastal erosion were conducted in the southern region, because of its long shoreline and hilly terrain. Thus, for each sector, there were many published papers focusing on those regions where specific disaster risks are high.

Papers on 'Thailand' accounted for 10%–30% of those for every sector. Thus, for each sector some of the studies were conducted not only in a particular sub-region but also at a multi-regional or nationwide scale.

Of the studies that included results outside Thailand, most that targeted Southeast Asia focused on forest hydrology, because of the marked land-use changes and deforestation in the Indochina Peninsula. There was also a large percentage of studies on agricultural hydrology, given that agriculture is a key industry in many Southeast Asian countries. Since the Mekong is an international river, many of the regional studies examined riverine hydrology. The rapid rate of urbanization in Southeast Asia was reflected by the many studies that addressed urban hydrology. Only a few studies were on coastal erosion but many of them focused on Asia (table 1). Three papers examining agriculture targeted not only Southeast Asia but other parts of Asia as well. Those studies examined the impacts of climate change on rice, which is a major agricultural product throughout Asia. The high fraction of global studies of sediment-related topics reflected the fact that studies of landslides in Thailand were frequently cited as references in studies of other regions outside the country.

It should be noted that the numbers of search results varied among the sectors (table 1). In particular, there were relatively few papers on sediment and

coastal erosion, such that the regional characteristics of these topics could not be sufficiently extracted. Further studies of those topics are needed.

Regional analyses highlighted the link between sectors. For example, the large number of studies in the northern region that focused on the sectors riverine hydrology, sediment, and forest hydrology implies inter-sectoral risks and therefore the need for a risk-oriented synthesis, as discussed in the following section.
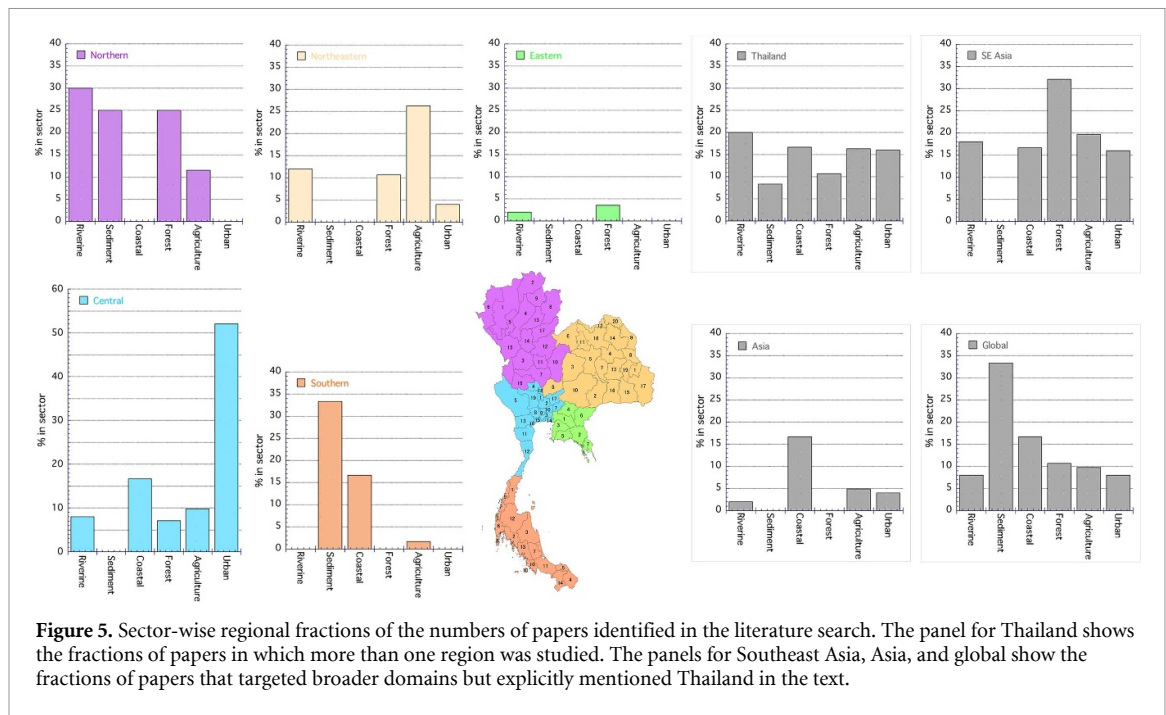
5.2. Risk-oriented synthesis based on impact assessments in each sector

In this section, the findings of sections 3 and 4 are reconsidered from a risk point of view. Our focus is on four potential disasters relevant to water resources and their management: drought, flood, coastal erosion and landslide. The following analysis considers the physical connections among individual sectors.

5.2.1. Drought

Thailand is vulnerable to drought, which occurs in the dry season (from November to April). The high air temperatures and abundant solar insolation during these months are favorable for agriculture but there is little rainfall and crops must be irrigated, primarily with water provided by large dams. The amount of water available at the beginning of the dry season depends on the total inflow during the preceding wet season (from May to October) and on dam operation. To maximize the amount of irrigation water, the volume of water stored in the dams during the wet season should be kept as high as possible. However, this jeopardizes the dams' capability of flood control, which is often necessary during the second half of the wet season. Since reliable and quantitative rainfall and streamflow forecasts for several months ahead are not possible, dam operation is still very much a process of trial and error to avoid not only flooding but also water shortages. Reservoir capacity in the Chao Phraya River system in northern and central Thailand exceeds 24 billion m³ (Lehner *et al* 2011) whereas that in the Mun River system in northeastern Thailand is <10 billion m³. Thus, agriculture in northeastern Thailand is vulnerable to drought because of its greater dependency on rainfall.

The average precipitation in Thailand will likely increase in response to climate change, but changes in the Asian monsoon system (i.e. rainy and dry seasons) remain largely unexplored (section 3.2.2). The studies that assessed the changes in low flows (i.e. streamflow in the dry season) in response to climate change consistently reported decreases in streamflow (section 4.1.3.1). In addition, the demand for irrigation water is expected to increase in response to higher temperatures (section 4.5.3.1). Another concern is the predictions of earlier impact assessments that the yield of paddy rice, which is the major crop in Thailand,

Figure 5. Sector-wise regional fractions of the numbers of papers identified in the literature search. The panel for Thailand shows the fractions of papers in which more than one region was studied. The panels for Southeast Asia, Asia, and global show the fractions of papers that targeted broader domains but explicitly mentioned Thailand in the text.

will decrease due to higher air temperatures (section 4.5.3.1). Projections of inflows to dams during the wet season are uncertain and depend on the adopted GCM (section 4.1.3.1). However, our literature search revealed few studies on the enhancement of reservoir capacity and operation (section 4.1.3.2). Based on the assessments available to date, a higher drought risk in the dry season can be expected, worsened by a decrease in irrigation water availability and an increase in water demand.

5.2.2. Flooding
Thailand is vulnerable to flooding as well, typically late in the wet season (from September to October). In southern Thailand, with its mountainous terrain, flash floods often occur after intensive rainfall. In northern, central, and northeastern Thailand, flood waters travel relatively slowly but sometimes destructively, because of the gentle slope and extensive catchment areas of the basins of the Chao Phraya and Mun rivers. Bangkok, the capital and the largest city in Thailand, is located near the mouth of the Chao Phraya River. The drainage of local runoff is hindered by the low altitude (mean of 2 m above sea level), flat terrain, and the effects of tidal waves.

Increases in high flows, resulting in increases in the high-water level of the Chao Phraya River and the hazard of river floods, were predicted by all of the reviewed studies that addressed this topic (section 4.1.3.1). Bangkok will be vulnerable to additional flood inundation because of sea-level rise; the inundated area is projected to increase by 26% in 2050 under a sea-level rise of 32 cm and by 81% in 2100 under a sea-level rise of 88 cm compared to the area inundated by the flood event of 1995 (section 4.6.3).

These assessments project a synergetic impact on the increased flood risk.

Scenarios of future land use, despite their considerable uncertainty (section 4.4.3.1), predict a significant contribution of land-use changes to runoff. Indeed, the impact of land-use type may be even greater than that of climate change. With appropriate land-use planning as an adaptation, the flood risk may be controllable at a national level whereas mitigating the impacts of climate change requires a global effort.

5.2.3. Coastal erosion
The long coastline of Thailand, much of it consisting of sandy beaches, attracts a large number of tourists from around the world and is an important economic resource. Sandy beaches are formed by the transport of sediments from rivers and via the actions of coastal tides and waves. The Chao Phraya River, which is the largest river flowing into the Bay of Thailand, is a highly developed basin and the transport of its sediments is largely hampered by the many large dams and weirs controlling its flow.

The sea-level rise caused by climate change will cause a shoreline retreat of up to 72% (39 km^2) of the total sandy beach area, according to some projections (section 4.3.3.1). Rapid population growth and asset accumulation in the low-lying areas of many coastal cities (including Bangkok) will increase the risk of coastal erosion (section 4.3.3.2). Taken together, these events and actions will increase the risk of coastal erosion and worsen its impacts.

5.2.4. Landslide
Mountainous northern and southern Thailand are vulnerable to sediment disasters. Changes in rainfall

and land cover are important determinants of the risk of landslide disaster. Although cutting natural forest is legally banned[39], traditional slash-and-burn agriculture in affected regions continues. These haphazard forest cutting and cultivation practices in Thailand's mountainous provinces have increased the risk of land sediment disasters.

The projected increases in precipitation amounts will be the main contributor to the higher disaster risk of landslides (section 4.2.3). Because precipitation intensity differs spatially, including in mountainous areas that are particularly vulnerable to landslides (section 4.4.2.1), further development and distribution of dynamically downscaled precipitation scenarios with more spatiotemporally detailed data (section 3.2.4) will lead to advances in this research field. To support such RCM assessments, a reliable and dense hydrometeorological network is needed (section 4.4.2). For the topics of land use and de/afforestation, our literature search included a number of scenario analyses but such studies are still in their infancy (section 4.4.3). Importantly, although landslides accelerate sedimentation in dams and rivers, decrease the storage and flow capacity, and increase drought and flood risks, there has yet to be a major study of these related phenomena.

6. Research recommendations

The sector-wise reviews in sections 3 and 4 together with the cross-sector analysis in section 5 identified several items that are improving studies of the impact of climate change on the water sector in Thailand.

6.1. Online distribution of long-term observation data

In Thailand, reliable data are collected via extensive monitoring networks for meteorology, river features (water level and streamflow), landslides, coastal erosion, and urban climate and hydrology. Short-term up-to-date data (typically covering several hours to a week) are widely available on the websites of the agencies in charge and are mainly employed to formulate public disaster warnings. However, the efforts of researchers have been hindered by limited access to long-term historical data. For example, in some cases the data are still published in printed year books but a switch to a PDF format available online would greatly enhance the accessibility of the data. The establishment of an online database system enabling public access to all the historical data would accelerate not only hydrometeorological studies but also various artificial intelligence applications.

For several fields, the data were insufficient to allow detailed analyses. For example, there has been little hydrometeorological monitoring in mountainous regions, although this information is critically important in assessments of the hydrometeorological alterations imposed by climate change, land-use change, and other factors. Data on water use, in particular irrigation water withdrawal, are also scarce. Further efforts are needed to expand the monitoring network and improve the reliability of hydrological data.

6.2. Data reconstruction and trend and extreme value analyses based on solid statistical techniques

Historical observations are crucial in the fields of Earth Science and Environmental Science as they reveal past patterns of change. Perhaps the most fundamental variables that should be monitored are air temperature and precipitation. Among the included reviews, the trends and extreme values reported in the studies tended to agree with respect to air temperature but were inconsistent for precipitation. This discrepancy can be primarily attributed to differences in the data used and will be resolved by rigorous statistical analyses.

The research community tends to wait for the disclosure of ready-to-use data but this passive attitude delays data analyses. Community efforts at data retrieval (e.g. Kuraji *et al* 2009), data compilation (e.g. Yatagai *et al* 2009), and data quality checking and re-gridding (e.g. Kotsuki *et al* 2014) have greatly enhanced climate-change impact studies but further, accelerated efforts are still needed.

6.3. Rapid online distribution of dynamic downscaling data related to climate change projections

In several studies, dynamic downscaling was conducted to obtain climate projections with spatiotemporal details (e.g. Manomaiphiboon *et al* 2013), but the accessible outputs of those simulations were limited. In fact, few of the studies included in our review contained impact assessments that utilized dynamically downscaled climate scenarios (Boonwichai *et al* 2018).

In contrast to GCMs, in many cases, the outputs of RCMs are limited in their distribution. Rapid online distribution of dynamic downscaling data for climate projections and of the supporting documents is necessary for advanced impact assessments. In addition, utilization of the data for further impact assessments requires well-described simulation settings and a minimum set of simulations that includes at least a decade of simulations for baseline (historical), high-end (e.g. RCP8.5) and low-end (e.g. RCP2.6) future periods.

Not only dynamic but also statistical downscaling are useful for many types of impact studies. Watanabe *et al* (2014) developed a future gridded climate scenario based on the statistical downscaling techniques for nine GCMs and made their work publicly accessible.

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[39] www.env.go.jp/nature/shinrin/fpp/communityforestry/index1.html

6.4. Rigorous and systematic comparisons of intensively studied topics

For some research areas, there were multiple peer-reviewed papers on the impact of climate change. These included projections of the discharge of important rivers, flood and drought risks, landslides, coastal erosion, rice crop yield, and others. A specific example is the runoff response to climate and land-use changes. However, the results presented in those papers were seldom compared with the findings of earlier studies. Our review of riverine hydrology and the information in supplemental table S1 together provide a good overview of earlier studies of this sector. Rigorous and systematic comparisons of the data from well-studied topics will avoid research redundancy and identify uncertainties in the projections. In addition, the establishment of harmonized simulation protocols would be useful for systematic model intercomparisons and multi-model assessments.

6.5. Intensive methodology development for less intensively studied topics

In contrast, peer-reviewed impact assessments were limited to analyses of weather and climate factors other than air temperature and precipitation, water demand (e.g. irrigation water demand), hydrological changes in specific areas (e.g. forests, mountains), etc. For these topics, the intensive development of methodologies is still needed.

6.6. Economic and multi-sectoral analyses for stakeholders

Another area of deficiency is in-depth impact assessment. Translating physical effects into economic and socioeconomic impacts is crucial to support decision-making by stakeholders (e.g. Takakura *et al* 2019). Moreover, the simultaneous occurrence of multiple impacts results in compounding effects (e.g. Mora *et al* 2018). Integrated models covering multiple sectors will facilitate analysis of the synergies and trade-offs of various countermeasures.

6.7. Filling the regional gaps in impact assessments

Studies on the impacts of climate change are plagued by considerable regional biases (section 5.1). Although the most intensively studied regions of Thailand have been those that are the most vulnerable to the impacts of climate change, the risks involve the entire nation. A straightforward approach is to assess the impacts of climate change on the entire country. For national models, in addition to the development of computer software and implementation of simulations, two types of data are essential: climate data for the entire nation that cover a time span from the past to the future, and which have been developed via community efforts; and reliable reference data for calibrating and validating the models. Nationwide observation data that are evenly distributed are essential to obtaining accurate estimates. National

impact assessment is beneficial for three major reasons. First, such assessments provide fundamental scientific information to local governments across the nation. Local governments play a key role in adaptation planning and implementation, but often lack the capability to conduct their own research. Second, it illustrates the distribution of potential risks. National assessments can identify the most vulnerable areas within the country. Third, by overlaying the risk maps of multiple sectors, risk hotspots, where risks are high for multiple factors (Piontek *et al* 2014), can be identified and risks related to various factors can be compared.

6.8. Integrated assessments of key disaster risks

Potential disasters in the water sector consist of drought, flood, coastal erosion, and sediment erosion. While assessments have focused on the direct impacts of climate factors, the risk of any one may be enhanced or negated by various indirect, non-climatic factors. Accordingly, in the case of drought, for example, data on surface water, groundwater, water withdrawal and use, and the operation of water-management facilities (e.g. dams and weirs) must be integrated. Similarly, in the case of flooding, data on surface water, river routing, and inundation are essential. Because, as discussed above, some of Thailand's large reservoirs play considerable roles in flood control, as evidenced by the flood in 2011, the effects of dams must be included in risk assessments. In the case of coastal erosion, not only the fundamental coastal erosion process (Bruun rule) but also sediment transport via rivers and tides as well as the interruption of transport due to damming must be included. Among the important considerations in sediment erosion, the connections between precipitation and landslides and the amount of vegetation coverage are decisive. Furthermore, for all of these disasters, land use and the distributions of population and assets play crucial roles. Consequently, integrated assessments will lead to a holistic understanding of climate risks and thus enable effective climate-change adaptation. We also note the importance of cross-sector integration to combat risks. Compound effects (Zscheischler *et al* 2018, Mora *et al* 2018), for example of wildfire under drought conditions (Australian Government Bureau of Meteorology 2020) or storm surge during a flood (Bevacqua *et al* 2019), are of serious public concern. The socioeconomic consequences of disasters are also concerning, but are especially difficult to estimate due to their links to numerous factors.

6.9. Enhancing collaboration for data collection and provisioning among experts

Reliable data are the foundation of research. Through an open data policy, most government agencies in Thailand accelerate the provision of data relevant to climate change and adaptation. Several ongoing actions of the TMD, RID, HII and ADAP-T are

described in supplemental text 1 and supplemental figure S1. Hydro-meteorological data are collected regularly in various places and under different conditions. However, a quality check and the removal of erroneous data are essential to maintaining the reliability of the data, a task that requires hydro-meteorological experts. Moreover, the volume of data is steadily growing, such that data collection and distribution require skilled information technologists. Better collaboration between these two types of expertise would be beneficial to researchers and government agencies.

Spatially extensive and long-term hydro-meteorological observations are the work of governmental agencies, whereas academics and researchers are responsible for the dissemination of knowledge regarding the latest advances in science and technology. The networking of these two communities should be further enhanced, such as through joint projects. For example, all the authors of this review are involved in the ADAP-T project. Both the 5 year ADAP-T project and the preceding IMPAC-T project demonstrate the enormous potential of government-university collaborations in Thailand.

6.10. Implementing research achievements in the real world

The implementation of measures aimed at climate change adaptation is the responsibility of not only central but also local government officers as well as multi-level stakeholders. Measures designed to mitigate climate change must be implemented top-down, and those of adaptation bottom-up. For the latter, the opinions of the many stakeholders must be taken into account. For instance, when the ADAP-T project installed a simple early warning system in landslide-disaster-prone areas, researchers and officers in the sediment sector team conducted small workshops with residents, local government officers, and officers in the local branch of several central governmental agencies (Jaikaeo *et al* 2013). This was one of several good practices tried and tested in Thailand and potentially relevant for other landslide-prone areas both in Thailand and in other countries of the Indochina Peninsula.

7. Policy implications

7.1. General strategy of flood management

In the politically and economically important urban areas of the Chao Phraya basin, infrastructure, such as dykes and drainage, has been put in place to provide flood protection. However, to some extent this has been done by neglecting flooding in rural areas (Morita *et al* 2013). Since the slope below the midstream region of the basin is very gentle, there are few areas suitable for dam construction. Instead, the strategy has been to allow the flood water to spread across a larger area, which results in its faster evaporation (Komori *et al* 2012). For rural residents, adaptation to this practice has included floating cultivation of rice and construction of houses that are two stories high.

With technical innovations and economic growth, new challenges in water-resource management have arisen. For example, the green revolution of the 1960s introduced high-yield varieties of rice. As these high-yield rice varieties have stems that are shorter than those of floating rice, they can be cultivated only in places with low water levels. Furthermore, high-yield rice is traded at a higher price than floating rice. Thus, farmers now require that the maximum depth of water in paddy fields is suitable for the cultivation of high-yield rice varieties (Morita *et al* 2013).

With the increased economic growth in Thailand, people have acquired more personal assets, which means that yearly floods have increased the financial extent of the damage (Tahira and Kawasaki 2015). This is expected to become a more serious problem with further economic growth, urbanization, and the extreme phenomena accompanying climate change. Thus, although rural areas have been utilized as water-retention areas, with their increasing prosperity alternative approaches to the management of flooding area and depth are required.

7.2. General strategy of water resource management

Due to the distinct difference between the wet and dry seasons, securing water resources throughout the year is challenging in Thailand. This review confirmed that this challenge will be exacerbated by climate change, which will cause drier dry seasons and wetter wet seasons. Reduction of water usage and expansion of its storage are key requirements for adaptation. The Strategic Plan on Thailand's Water Resources Management was established to mitigate unforeseen water shortages during the dry season and flooding during the wet season (The Policy Committee for Water Resources Management 2015). Its key strategies and targets are: to increase the efficient water management of the 5 million ha in existing irrigation areas, to increase the efficiency of existing water-resource projects by at least 10% for existing irrigation areas (~20% of total cropped land), and to develop new water-resource projects to achieve a volume of 9500 million m^3 and thereby increase irrigation to cover 1.4 million ha in 25 river basins. The strategic plan can be considered as a list of adaptation actions to climate change.

7.3. General remarks on adaptation policy

The major bottlenecks in the formulation of policies addressing climate-change vulnerability and adaptation are the reliability and validity of research

results. Uncertainties in climate scenarios pose a major constraint to the development of impact scenarios (ONEP 2010). Furthermore, at the local government level, determining which climate change activities and investments are needed depends on the level of knowledge and awareness that local leaders possess (Overseas Development Institute 2012). Adaptation measures have been developed at the national level but there are still gaps related to their implementation. This will require a multidisciplinary approach that includes protecting socially and economically vulnerable segments of society (The Thailand Research Fund 2016).

8. Concluding remarks

This comprehensive literature review on climate-change impacts and adaptation measures in Thailand focused on meteorology and six water-related sectors: riverine hydrology, sediment erosion, coastal erosion, forest hydrology, agricultural hydrology, and urban hydrology. The results can be summarized as follows: First, we found that over the past several decades considerable efforts have been made by governmental agencies to monitor hydrometeorological and related variables throughout the country. However, the data have mostly been used for the development of short-term measures, with less attention paid to sharing the long-term quality-checked data that are essential for detecting and monitoring the impacts of climate change. This limited availability of long-term hydrometeorological records together with insufficient efforts to reconstruct historical data account for the scarcity of studies on the changes in hydrometeorological indicators (precipitation, streamflow, etc) and other relevant variables (rice crop yield, sediment erosion, etc) likely to occur in response to climate change. The many peer-reviewed studies included in our review, while addressing all six sectors, nonetheless suffered from two key limitations. First, the studied areas were regionally biased by sector, such that studies covering the entire nation are still needed. Second, most of the studies examined a single hydrometeorological or bio-physical phenomenon (runoff, crop yield, etc) and therefore lacked the integrated approach that is essential for risk management (flood and drought damage mitigation, securing and improving farmer's livelihood). To improve studies on climate-change impacts in Thailand and elsewhere, the following recommendations can be made: further utilization of climate projections by RCMs; comparisons among impact models and harmonization of scenario analysis; the promotion of basic research in research fields for which modeling techniques are still not established, including economic and multi-sectoral assessments; the development of models that cover the entire nation; comprehensive risk assessments for flood, drought, sediment erosion, and coastal erosion;

and better collaboration between experts in different fields (e.g. scientists and data engineers) and professions (e.g. academic researchers and governmental officers).

In response to climate change, not only mitigation but also adaptation measures are being mainstreamed in most countries (UNFCCC 2018). Underlying these efforts is the generation of reliable data and scientific evidence. Timely compilations of this information are crucial for its practical application. To the best of our knowledge, this study is the first comprehensive review of the impacts of climate change on the water sector in Thailand. While our findings are intended to provide state-of-the-art knowledge for researchers and governmental officials in Thailand, they may also be useful for individuals and agencies in Myanmar, Laos, and Cambodia, countries with similar climatic and geographic characteristics.

Data availability

The data used for preparing the figures in this study are archived at The University of Tokyo (http://hdl.handle.net/2261/00078953). Archiving of the land-use data used for figure 1(c) is not permitted by the data provider.

Kiguchi, M. *et al*: Data for 'A review of climate-change impact and adaptation studies for the water sector in Thailand', the University of Tokyo, doi:10.15083/00078953

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.15083/00078953.

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Appendix A. Provinces in Thailand and their river basins with reference to figures 1(a) and (b).

Table A1. List of provinces shown in figure 1(a). The consecutive numbers for each region correspond to the numbers in figure 1(a).

North (purple)		10	Nakhon Ratchasima	17	Saraburi
1	Chiang Mai	11	Nong Bua Lam Phu	18	Sing Buri
2	Chiang Rai	12	Nong Khai	19	Suphan Buri
3	Kamphaeng Phet	13	Roi Et		
4	Lampang	14	Sakon Nakhon	East (light green)	
5	Lamphun	15	Si Sa Ket	1	Chachoengsao
6	Mae Hong Son	16	Surin	2	Chanthaburi
7	Nakhon Sawan	17	Ubon Ratchathani	3	Chon Buri
8	Nan	18	Udon Thani	4	Prachin Buri
9	Phayao	19	Yasothon	5	Rayong
10	Phetchabun	20	Bueng Kan	6	Sa Kaeo
11	Phichit			7	Trat
12	Phitsanulok	Central (light blue)			
13	Phrae	1	Ang Thong	South (orange)	
14	Sukhothai	2	Phra Nakhon Si Ayutthaya	1	Chumphon
15	Tak	3	Bangkok Metropolis	2	Krabi
16	Uthai Thani	4	Chai Nat	3	Nakhon Si Thammarat
17	Uttaradit	5	Kanchanaburi	4	Narathiwat
		6	Lop Buri	5	Pattani
Northeast (yellow)		7	Nakhon Nayok	6	Phangnga
1	Amnat Charoen	8	Nakhon Pathom	7	Phatthalung
2	Buri Ram	9	Nonthaburi	8	Phuket
3	Chaiyaphum	10	Pathum Thani	9	Ranong
4	Kalasin	11	Phetchaburi	10	Satun
5	Khon Kaen	12	Prachuap Khiri Khan	11	Songkhla
6	Loei	13	Patchburi	12	Surat Thani
7	Maha Sarakham	14	Samut Prakan	13	Trang
8	Mukdahan	15	Samut Sakhon	14	Yala
9	Nakhon Phanom	16	Samut Songkhram		

Table A2. List of river basins shown in figure 1(b). The consecutive numbers correspond to the numbers in figure 1(b).

1	Mae Nam Sarawin	10	Mae Nam Chao Phraya	19	Mae Nam Petchaburi
2	Mae Nam Khong	11	Mae Nam Sakae Krang	20	Prachuabkhiri-Khun
3	Mae Nam Kok	12	Mae Nam Pasak	21	East Coast
4	Mae Nam Chi	13	Mae Nam Tha Chin	22	Mae Nam Tapi
5	Mae Nam Mun	14	Mae Nam Mae Klong	23	Thale Sap Songkhla
6	Mae Nam Ping	15	Mae Nam Prachin Buri	24	Mae Nam Pattani
7	Mae Nam Wang	16	Mae Nam Bang Pra Kong	25	West Coast
8	Mae Nam Yom	17	Tonle Sap		
9	Mae Nam Nan	18	East Coast Gulf		

Appendix B. Glossary

ADAP-T	Advancing Co-design of Integrated Strategies with Adaptation to Climate Change in Thailand
AR5	Fifth Assessment Report
BMA	Bangkok Metropolitan Administration
CMIP5	Coupled Model Intercomparison Project Phase 5
CORDEX-SEA	Coordinated Regional Climate Downscaling Experiment-Southeast Asia
DWR	Department of Water Resources
GCM	Global Climate Model
HII	Hydro-Informatics Institute
IPCC	Intergovernmental Panel on Climate Change
MoNRE	Ministry of Natural Resources and Environment
MRI	Meteorological Research Institute
NAP	National Adaptation Plan
ONEP	Office of Natural Resource and Environmental Policy and Planning
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RID	Royal Irrigation Department of Thailand
SEACLID	Southeast Asia Regional Climate Downscaling
TMD	Thai Meteorological Department

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