Department of Civil and Environmental Engineering

Hydrological changes in the Mekong River Basin

The effects of climate variability and hydropower development

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Timo A. Räsänen

Aalto University

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Hydrological changes in the Mekong River Basin

The effects of climate variability and hydropower development

Timo A. Räsänen

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Abstract

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Abstract

The world's large rivers are increasingly exploited for human use and are affected by changes in global climate. Dams, the consumptive use of water and a changing climate have resulted in river fragmentation and flow alteration on a global scale. The Mekong River Basin has been one of the world's less affected large rivers, but recently the development has started to shape the river. In the Mekong, the livelihoods, the economy and food security are closely connected to the river environment and its productivity. The productivity in turn is largely driven by the hydrology. Therefore, an understanding of the ongoing hydrological changes is crucial.

This dissertation aims at fulfilling hydrological research gaps in the Mekong. These research gaps concern the climate induced hydrological variability and the impact assessment of hydropower development in the Mekong. The main research framework of this dissertation is based on hydrology and water resources research and the methods are based on statistical and mathematical models. In addition, the dissertation discusses the role of disciplinarity in the hydrological knowledge production.

The dissertation found that the Mekong's hydrology has been strongly influenced by El Niño – Southern Oscillation (ENSO), and that in recent decades the Mekong's hydrological variability has increased to levels that may not have been experienced within the past 700 years. The recent increase in hydrological variability was, at least partially, attributed to an increase in ENSO activity. The dissertation developed new assessment approaches for assessing hydropower development and found that river flows will be considerably affected and this development leads to increasing complexity and trade-offs among different sectors of society. In addition, it was found that climate variability and the development of the water resource infrastructure result in cumulative impacts that need further attention.

Altogether, the dissertation concludes that the Mekong has entered a new hydrological era, where humans have become a major force transforming the Mekong's hydrology. The ongoing hydrological changes are likely to have an impact on ecology, livelihoods and food security. This new era requires new holistic planning and assessment processes, and in the case of hydrological and water resources research and education, the dissertation recommends the recognition of complexity, uncertainty, and co-operation across disciplines and societal sectors as future directions.

Keywords Mekong, Hydropower, Climate Variability, Hydrological Impact Assessment

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Tiivistelmä

Maailman suuria jokia hyödynnetään entistä enemmän ihmisten tarpeisiin. Samaan aikaan ilmastovaihteluiden ja ilmastonmuutoksen vaikutukset ovat lisääntyneet. Mekong-joki on yksi harvoista maailman suurista joista, joka on saanut virrata lähes luonnonmukaisesti viime vuosikymmeniin saakka. Mutta viime vuosina patorakentaminen sekä maatalouden vedenotto ovat lisääntyneet merkittävästi. Mekong-joella muutokset ovat merkittäviä, koska alueen talous, elinkeinot ja ruokaturva kytkeytyvät läheisesti veteen.

Tässä väitöskirjassa tarkastellaan ilmastovaihteluiden ja vesivoimarakentamisen aiheuttamia hydrologisia muutoksia ja pyritään kuromaan umpeen niihin liittyviä tutkimusaukkoja. Väitöskirjatutkimus perustuu hydrologian ja vesitalouden tutkimusaloihin, ja se soveltaa tilastotieteeseen sekä matemaattiseen simulointiin ja optimointiin perustuvia menetelmiä. Tämän lisäksi väitöskirjassa tarkastellaan hydrologiseen tutkimusprosessiin liittyviä seikkoja, jotka vaikuttavat tuotetun tiedon luonteeseen ja soveltamiseen.

Väitöskirjan ilmastovaihteluihin keskittyvä osio osoitti, että Mekong-joen valuma-alueen hydrologisia vaihteluita on ajanut voimakkaasti El Niño – eteläinen värähtely (ENSO). Viime vuosikymmeninä lisääntynyt ENSO-aktiivisuus on lisännyt myös hydrologisia vaihteluita. Vastaavan suuruisia hydrologisia vaihteluita ei ole tapahtunut mahdollisesti 700 vuoteen. Väitöskirjassa kehitetyt uudet lähestymistavat vesivoimarakentamisesta syntyvien virtaamamuutosten vaikutusten arviointiin ennustavat merkittäviä virtaamamuutoksia Mekong-joelle. Tutkimustapaukset osoittavat myös, että vesivoimarakentaminen tekee vedestä entistä hallinnoidumman resurssin, mikä voi johtaa lisääntyvään kilpailuun vedestä. Ilmastovaihteluiden ja patorakentamisen havaittiin myös synnyttävän kumulatiivisia hydrologisia muutoksia, joiden arviointiin on syytä keskittyä.

Väitöskirjan johtopäätöksenä on, että Mekong-joella on alkanut uusi aikakausi: ihmisestä on tullut merkittävä hydrologinen muutostekijä ja meneillään olevat muutokset uhkaavat alueen ekologiaa, elinkeinoja ja ruokaturvaa. Tämä uusi aikakausi vaatii vaikutusten arviointiin ja kehityksen ohjaamiseen tähtäävältä tutkimukselta uusia kokonaisvaltaisempia lähestymistapoja. Hydrologisen tutkimuksen ja opetuksen kannalta tämä tarkoittaa erityisesti kompleksisuuden ja epävarmuuden hallintaa sekä tiiviimpää yhteistyötä eri tieteenalojen ja yhteiskunnan tahojen välillä.

Avainsanat Mekong-joki, vesivoima, ilmastovaihtelut, hydrologinen vaikutusten arviointi

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CONTENTS

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Helsinki, 3rd of July

Timo Räsänen

LIST OF APPENDED PAPERS

The dissertation is based on the following papers:

I: Räsänen, T.A., Kummu, M. 2012. *Spatiotemporal influences of El Niño-Southern Oscillation (ENSO) on precipitation and flood pulse in the Mekong River Basin*. Journal of Hydrology, 476(7):154-168.

II: Räsänen, T.A., Lehr, C., Mellin, I., Ward, P.J., Kummu, M. 2013. *Palaeoclimatological perspective on river basin hydrometeorology: case of the Mekong*. Hydrology and Earth System Sciences, 17, 2069-2081.

III: Räsänen, T.A., Koponen, J., Lauri, H. and Kummu, M. 2012. *Downstream hydrological impacts of hydropower development in the Upper Mekong Basin*. Water Resources Management 26(12): 3495-3513.

IV: Räsänen, T. A., Joffre, O. M., Someth, P., Thanh, C. T., Keskinen, M., and Kummu, M. (2014). *Model-based assessment of water, food, and energy trade-offs in a cascade of multipurpose reservoirs: Case study of the Sesan tributary of the Mekong River*. Journal of Water Resources Planning and Management, doi:10.1061/(ASCE)WR.1943-5452.0000459.

Papers I-IV are reprinted with permission and copyrighted as follows:

CONTRIBUTION OF THE AUTHOR TO THE PAPERS

I. The author is mainly responsible for the design of the research, fully responsible for collecting the data and performing the data quality assurance, fully responsible for performing the analyses, fully responsible for analysing the results, and mainly responsible for the writing of the paper. Prof. Kummu supervised the research process and participated in the design of the research and in the writing of the paper.

II. The author is mainly responsible for the design of the research, fully responsible for collecting the data, mainly responsible for performing the analyses, mainly responsible for analysing the results, and mainly responsible for the writing of the paper. Lehr performed the wavelet analyses and participated in the analysis of wavelet analyses results and in the writing of the paper. Dr. Ward contributed by providing guidance for palaeoclimatological research and by participating in the writing of the paper. Mellin supervised and provided guidance for the statistical analyses and participated in the writing of the paper. Prof. Kummu supervised the research process and participated in the design of the research and in the writing of the paper.

III. The author is mainly responsible for the design of the research, fully responsible for collecting hydrological and hydropower data, fully responsible for recalibration of the hydrological model, fully responsible for the setup of the hydropower model, fully responsible for performing all model simulations, fully responsible for analysing the results, and mainly responsible for the writing of the paper. Lauri and Koponen made the original setup and calibration of the hydrological model. Lauri also participated in the writing of the paper. Prof. Kummu supervised the research process and participated in the design of the research and in the writing of the paper.

IV. The author is mainly responsible for the design of the research, fully responsible for collecting the data for the hydrological and hydropower models, fully responsible for setting up the hydrological and hydropower model, fully responsible for running the hydrological and the final multi-purpose reservoir simulations, fully responsible for analysing the final multi-purpose reservoir simulation results, and mainly responsible for the writing of the paper. The author also provided hydrological data for land suitability and crop water requirement assessments. Joffre participated in the design of the research, performed the land suitability assessment together with Thanh, and participated in the writing of the paper. Dr. Someth participated in the design of the research, performed the crop water requirement assessment, and participated in the writing of the paper. Dr. Keskinen contributed by giving the results a broader societal context by participating in the writing of the paper. Prof. Kummu supervised the research process and participated in the writing of the paper.

“She has neither language nor discourse;
but she creates tongues and hearts,
by which she feels and speaks.”

-Goethe
(Huxley 1869)

1. INTRODUCTION

The world's large rivers are increasingly exploited for human uses (Vörösmarty et al. 2004; Vörösmarty et al. 2010). Dams and consumptive water use have resulted in river fragmentation and flow changes on a global scale (Haddeland et al. 2006; Lehner et al. 2011; Nilsson et al. 2005). In addition, the world's large rivers have been affected by global warming by changing the regional climates and impacting the hydrology of the rivers (Palmer et al. 2008). The large rivers are thus becoming increasingly affected by human actions and transformed into human-managed systems. Such situation exists also in the Mekong River Basin, which is the research area of this dissertation.

1.1. Mekong River Basin

The Mekong River Basin is located in mainland Southeast Asia. The basin has an area of 795,000 km^2 and is shared by China (21% of basin area), Myanmar (3%), Thailand (23%), Lao PDR (25%), Cambodia (20%) and Vietnam (8%) (MRC 2005) (Figure 1). The Mekong River originates from altitudes above 5000 m amsl (above mean sea level) on the Tibetan Plateau in China from where it flows through the deep and narrow mountain gorges of Yunnan in China, and the karst mountain regions of Lao PDR and enters the flood plains in Cambodia and the river delta in Vietnam. The river flows altogether over 4800 km before discharging its waters into the South China Sea (MRC 2005).

The Mekong is dominated mostly by a monsoon climate with distinct wet and dry seasons. The wet season starts at the onset of the monsoon rains in May and lasts until October (MRC 2005). The wet season is followed by the dry season from November until April. During the dry season period, rainfall is minimal and sometimes non-existent (MRC 2005). The average rainfall in the Mekong Basin is 1400 mm/yr and varies between different regions (300-3000 mm/yr) (Paper I).

The strong seasonal distribution of rainfall shapes the flow regime of the Mekong River, which can be described as a monomodal flood pulse (Junk et al. 1989; Junk et al. 2006). The monomodal flood pulse refers to a flow regime with a single annual flood season followed by a low flow season. For example, at Strung Treng in Cambodia, the peak flows of the wet season are on average 41,000 m^3/s, and the low flows of the dry season are on average 1800 m^3/s (Paper I). During the wet season, large land areas in the floodplains of Cambodia and Vietnam are annually inundated. The annual average flow of the Mekong is around 14,500 m^3/s, or 475 km^3/yr (MRC 2005), which makes it the 14th largest river in the world.

The pulsing flow regime of the Mekong has created ecosystems that are rich in biodiversity and highly productive. The Mekong is regarded as one of the world's richest inland fisheries (Baran et al. 2007; Baran and Myschowoda 2009), and it has biodiversity hot spots such the Tonle Sap Lake (see location in Figure 1) (Junk et al. 2006). The high aquatic productivity of the Mekong is also the source for the subsistence, livelihoods and food security of millions of people (MRC 2010). For example, it has been estimated that the aquatic ecosystems (i.e. fish and other aquatic animals) provide 47-80% of the animal protein intake for 56 million people in the region (Hortle 2007).

The Mekong Basin is, however, currently undergoing rapid development, which poses increasing pressures on water resources and aquatic ecosystems (Grumbine et al. 2012; Pech and Sunada 2008; Stone 2011). The population and economy are growing, which has resulted in increasing demand for energy and food. For example, the population of the basin has grown from 63 million in 1995 to 72 million in 2005, the energy demand increased during the period of 1993-2005 at an average annual rate of 8%, and the cereal demand is expected to double by the year 2050 (Pech and Sunada 2008). The increased energy demand in the riparian countries has resulted in massive hydropower construction in the basin. It is estimated that the number of dams in the Mekong may increase from the current 41 up to 160 dams in the future (Grumbine and Xu 2011; Paper III). The hydropower development would result in a total water-regulating capacity of over 100 km^3 (Paper III), which approximately corresponds to 20% of the Mekong's annual flow. In addition, agriculture is expected to expand into new areas and increase agricultural water withdrawals for irrigation (MRC 2010; Pech and Sunada 2008). Currently, over 4 million hectares of land is under irrigation in the Lower Mekong Basin (LMB; China and Myanmar excluded), which corresponds to 5% of the Mekong basin area (MRC 2010). The irrigation water abstraction is estimated to be 41.8 km^3, which corresponds to 8.8% of the annual flow of the Mekong. Irrigation is expected to increase in the future, especially during the dry season (MRC 2010).

In addition to hydropower and irrigation development, climate variability and climate change affect the hydrology, ecology, and societies in the Mekong. For example, recent years have experienced severe droughts (e.g. 1992, 1993, 1998, 1999 and 2003–2005) and floods (e.g. 2000, 2001, 2002 and 2011), which have affected the lives of millions of people (MRC 2010; MRC 2011a). In addition, the average temperatures and rainfall are expected to increase due to climate change, but uncertainties exist in the direction and magnitude of the change in river flows (Kingston et al. 2011; Lauri et al. 2012). However, recent flow analyses also suggest that the occurrence of extreme flow events has increased (Delgado et al. 2010), but whether this has been a result of climate change is not known.

The ongoing changes in the Mekong Basin will have an impact on its hydrology (Lauri et al. 2012) and sediment transport (Kummu et al. 2010), and consequently on aquatic environments (Lamberts 2008) and people's livelihoods (MRC 2010). A major concern has been on the impact on the productivity of aquatic ecosystems due to the high human dependency on them (Baran et al. 2007; Hortle 2007; MRC 2010). The water level changes caused by the hydropower development are expected to result in habitat changes and reduced productivity of aquatic ecosystems (Arias et al. 2014a; Arias et al. 2012). It is understood that hydrological variability is closely connected with agricultural productivity (Chinvanno et al. 2008; MRC 2010) and fish catch (Baran and Myschowoda 2009; Van Zalinge et al. 2004). Some estimates have been done that suggest that hydropower development may reduce 51% of the migratory fish biomass through a barrier effect (Ziv et al. 2012) and the total fish catch by 550-800 000 tons (ICEM 2010), which corresponds to the annual fish consumption of 19-27 million people (average consumption of 29.3 kg/capita/year (Hortle 2007)). Thus the understanding of the ongoing hydrological changes in the Mekong are important as they are strongly related to the livelihoods, economy and food security of millions of people in the region (Arias et al. 2014a; Baran et al. 2007; Hortle 2007; MRC 2010; Te 2007; Van Zalinge et al. 2004).

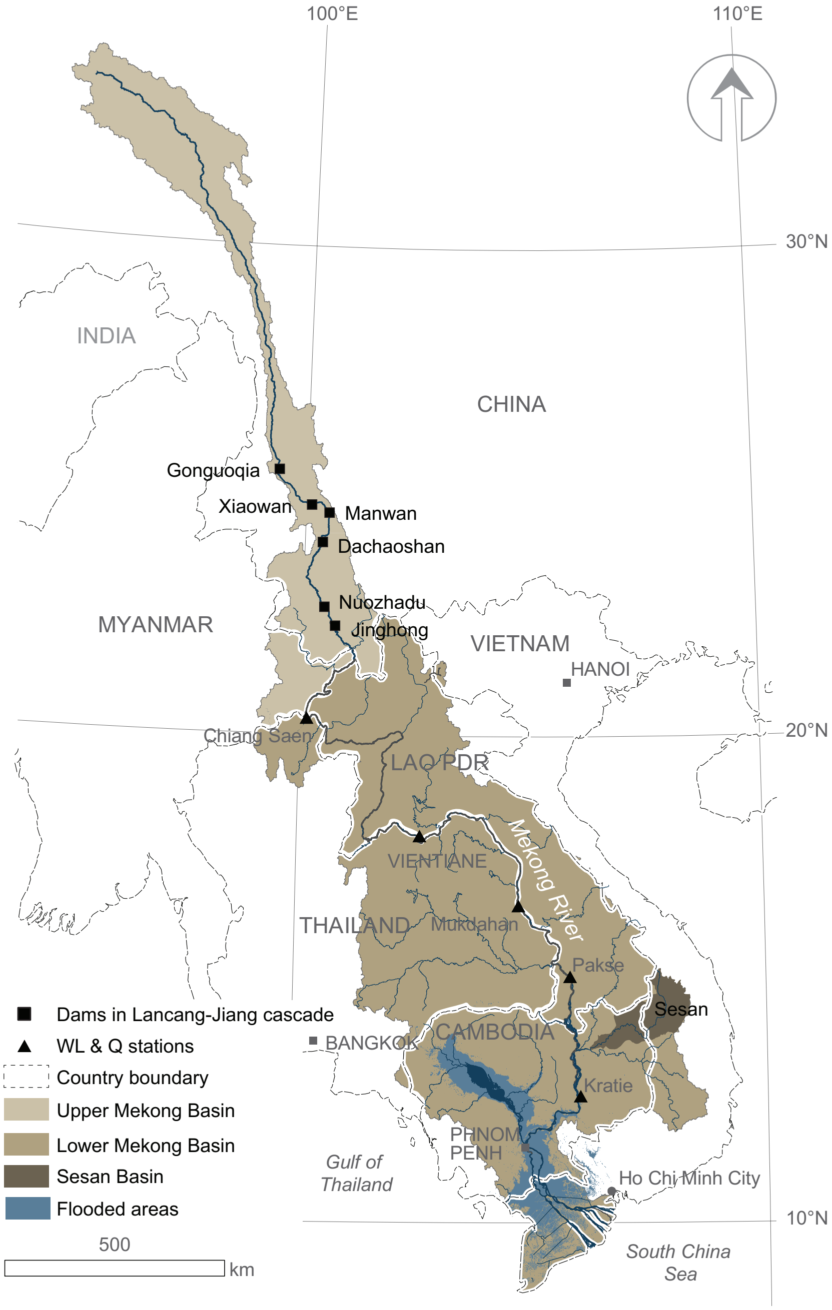


Figure 1. Map of the dissertation research area – the Mekong River Basin. Figure adapted from Paper III.

1.2. Research focus

The understanding of hydrological changes in the Mekong is increasing rapidly, but there are still several research gaps and this dissertation focuses on three of them:

I. Limited understanding of the role of ENSO in the hydrological variability in the Mekong Basin

II. Limited understanding in the long-term hydrological variability in the Mekong Basin

III. Lack of consideration of power production, cascade operation and multi-purpose operation in the river flow impact assessments of hydropower development in the Mekong

First research gap concerns scientific evidence on the role of climatic factors in hydrological variability, which has remained scarce in the Mekong although recent decades have experienced severe droughts and harmful floods (MRC 2010; MRC 2011a; Te 2007). One such climatic factor is El Niño - Southern Oscillation (ENSO) (Sarachik and Cane 2010), which is known to affect the hydrology world-wide (Ward et al. 2010) and also in Southeast Asia (Juneng and Tangang 2005). For example, the rainfall in mainland Southeast Asia, where the Mekong Basin is located, is driven by Indian Summer Monsoon (ISM) and Western North Pacific Monsoon (WNPM) and they are both weakened by El Niño events (Juneng and Tangang 2005; Wang et al. 2001; Wu and Wang 2002). In the case of the Mekong Basin, the research evidence on ENSO-hydrology relationship has been scarce. The river flow variability in the Mekong has been linked to variability in WNPM (Delgado et al. 2012), which provides a strong evidence on the connection between Mekong River and ENSO. The effect of ENSO in the Mekong has been observed also in the rainfall and discharge: during non-El Nino years the precipitation (discharge) was on average 8% (16%) higher than during El Nino years (Kiem et al. 2004; Xue et al. 2011). Evidence on ENSO's influence in the Mekong has also been found in river bank erosion rates: significant correlation exists between river bank erosion and ENSO and it has strengthened in the post 1980 period (Darby et al. 2013). The past research show that ENSO plays an important role in the Mekong, but there is no comprehensive understanding on how ENSO affects the spatial and temporal patterns of monsoon rainfall and the flood pulse and thus the droughts and floods of the Mekong.

Second research gap concerns the understanding of the long-term hydrological variability in the Mekong and how the recent variability, including the recent droughts and floods (MRC 2010; MRC 2011a; Te 2007), compares in longer time perspective. Little research has been done mainly because of limitations in the historical hydrological data that covers only the past hundred years, at most. Few studies have focused on long-term climate variability in Mainland Southeast Asia (Buckley et al. 2007; Buckley et al. 2010; Cook et al. 2010; Fan et al. 2008; Fang et al. 2010; Sano et al. 2009). Their methods are based on linking tree-ring chronologies to hydrological data, namely Palmer Drought Severity Index, or on interpreting the tree-ring chronologies directly. Their common finding is that climate and hydrology have varied in multi-annual and decadal scales. However, none of those studies focused on the hydrology on Mekong Basin scale or examined the recent hydrological variability in longer time perspectives.

Third research gap concerns the river flow impacts of hydropower development. The future impacts on flow regimes have been assessed by several studies, but important gaps exist in the assessments and in the assessment methods. On Mekong Basin scale two scientific assessments have been conducted (Lauri et al. 2012; Piman et al. 2013). They both used a model based approach to assess the flow regime impacts of 126-146 existing and future dams and found that the flow regimes of the Mekong will be considerably impacted: dry season flows will increase (25-160%) and wet season flows will decrease (5-24% in Kratie, Cambodia). The second study (Piman et al. 2013) included also the current and future irrigation and water supply demands in the assessments. Similar model based approaches for assessing the river flow impacts have been conducted in Mekong sub-catchment scale. For example, in Sekong-Sesan-Srepok sub-catchment at least three scientific studies have investigated these impacts all showing considerable increases in dry season flows and decreases in wet season flows (Arias et al. 2014b; Piman et al. 2012; Ty et al. 2011). The Major gaps in the earlier assessments have been that they have not considered more complex hydropower operations, such as power production driven operations, cascade operations and multipurpose operations in the modelling approaches and their impacts of flow regimes. The cascade operation refers to an operation mode where two or more hydropower projects co-operate. Multi-purpose operation refers to the use of water in the reservoir for other purposes in addition to hydropower. These gaps have resulted in limited understanding of for example the river flow impacts of the largest hydropower cascade in the Mekong, the Lancang-Jiang cascade in China and in the understanding of the cumulative river flow impact of irrigation and hydropower operation.

1.3. Objectives and research questions

The main objective of this dissertation is to fill the research gaps identified in Section 1.2. This is done through four scientific papers based on hydrological and water resources research. In addition, the dissertation recognises that single discipline approach based hydrological and water resources research provides only a partial view on the ongoing development in the Mekong River Basin. The consequences of such partial research views are not always recognised and openly stated although their influence on the research outcomes can be considerable (Max-Neef 2005; Pahl-Wostl 2007). Therefore, the secondary objective of this dissertation is to discuss the disciplinary aspects of the hydrological and water resources research.

The dissertation formulates four research questions, on the basis of the two objectives to which it aims to answer:

I. What kind of role does climate play in the Mekong's hydrological variability?

II. What kind of impacts does hydropower development have on river flows?

III. What are the potential cumulative impacts of water resources development and climate on the river flows?

IV. What implications disciplinarity and discipline specific standard methods (in this case statistics and mathematical models) have on the production and use of hydrological knowledge?

The first three research questions are answered through the research Papers I-IV and by further synthesising their findings. The fourth research question is tackled through discussion in the discussion section of the dissertation.

It is also important to acknowledge that the dissertation uses the concepts of discipline, disciplinarity, disciplinary approach, method and methodology with specific meanings: *discipline* refers to "a specific field of study that creates its own branch of scientific knowledge" (Keskinen 2010); *disciplinarity* refers to "mono-discipline" and generally represents specialisation in a single discipline (Max-Neef 2005); *disciplinary approach* refers to a research approach that is based on a single discipline; *method* refers to a specific way of collecting or analysing the data; and *methodology* refers to the broader research strategy that may include the use of specific methods.

1.4. Scientific framework

The main scientific framework of the dissertation is based on the *hydrology and water resources research* and follows the principles of the scientific method (Gauch 2012). The four research papers of this dissertation have been conducted using this main framework. The dissertation also has a secondary framework, which has been used in the discussion part and is based more on *philosophical reasoning*. The secondary framework was used to study the *knowledge production* process of hydrological research with the help of standard approaches of philosophy, such as logics and reasoning. The philosophical discussion was also complemented with the relevant literature. These two frameworks are introduced in the following sections.

1.4.1. Hydrology and water resources research

Hydrology studies the movement of water on the earth's surface (Dingman 2008). The main study components of hydrology are precipitation, surface waters such as river and lakes, soil water in unsaturated and saturated zones and evaporation. These components are linked together using the concept of the hydrological cycle, which describes the movement of water between land and atmosphere.

The basic principles of the hydrological cycle are as follows. When precipitation falls on the earth's surface, part of the water is evaporated from the soil, water surfaces and vegetation back to the atmosphere. Part of the water stays above the soil surface, forming rivers and lakes, and part of the water is infiltrated into the soil from where it seeps to rivers and lakes. The surface and soil water is then drained through rivers and other water bodies into the oceans, where water evaporates back into the atmosphere. The spatial unit, in which the hydrological analysis often occurs, is a river catchment or river basin. The river catchment is defined by using geographical features of the earth's surface, so that the catchment forms an area where all the precipitation that falls into the catchment is drained out of the catchment from a single output point.

Hydrology can be considered to be applied hydrology when the study of the hydrological cycle is included to cover human or other "external" interferences. This means the consideration of climate variability, human water use, water infrastructure development and other water resources management activities together with the components of hydrological cycle.

Water resources research considers water as a resource for human use and investigates their development and management. Typically water resources research examines the availability, distribution and management of water between different water users (e.g. hydropower and irrigation) as well as the impacts of water use on different water users. The research papers of this dissertation cover hydrology, applied hydrology and water resources research, but also include aspects from climatology and palaeoclimatology.

1.4.2. Knowledge production

Knowledge production is a term that is used commonly to describe knowledge production processes and their transformations. Knowledge production processes can be investigated from various perspectives, such as cognitive, organisational and external relations (Hessels and van Lente 2008), but at the core of the scientific knowledge production is the scientific method (Gauch 2012).

Gauch (2012) describes the scientific method consisting of the following elements: hypothesis formulation, hypothesis testing, deductive and inductive logic, controlled experiments, interaction between data and theory, and limitations of science's domain. He also remarks that there is no single unambiguous scientific method and its definition is controversial.

The knowledge production processes are also considered as being in transformation. The most famous investigations of the transformation of knowledge production processes are most likely the Structure of Scientific Revolutions, by Kuhn (1970), and Mode 2 by Gibbons et al. (1994). Various other investigations also exist, and some of them have been reviewed by Hessels and van Lente (2008). However, this dissertation has a more focused and practical approach on scientific knowledge production and their transformations than the cited studies. It specifically focuses on how the use of disciplinary approach and discipline specific standard methods (in this case statistics and mathematical models) affects the knowledge production process and the nature of the knowledge that is produced in the field of hydrology.

1.4.3. Philosophy

Philosophy can be described as a systematic method of investigating fundamental problems based on rational reasoning (Gauch 2012). A commonly used form of rational reasoning is logic. Although logical reasoning has many forms, the basic forms are inductive and deductive reasoning (Gauch 2012). Inductive reasoning draws generalisations from observed data, and deductive reasoning derives conclusions from a set of premises or general statements.

In simple terms, inductive reasoning can be said to progress from observation towards general theories, and deductive reasoning progresses from general theories to specific conclusions. Both forms of logical reasoning have certain assumptions that need to be acknowledged. Inductive reasoning assumes that the observed data is adequate to arrive at a reliable generalisation or theory, and deductive reasoning assumes that the premises on which the reasoning is based on are true. Statistical analysis is also a form of inductive reasoning, as it aims to draw broader generalisations on observed phenomena by extracting properties from data describing the phenomena.

1.5. Research Papers

The core of the dissertation is based on four research papers concerning the Mekong River Basin. The research Papers form two pairs with two lines of continuing stories. The first pair, Papers I and II, assessed the climate-related hydrological variability in the Mekong, while the second pair, Papers III and IV, assessed the impacts of hydropower development on the river flow. These Papers and their focuses are introduced below and summarised in Figure 2.

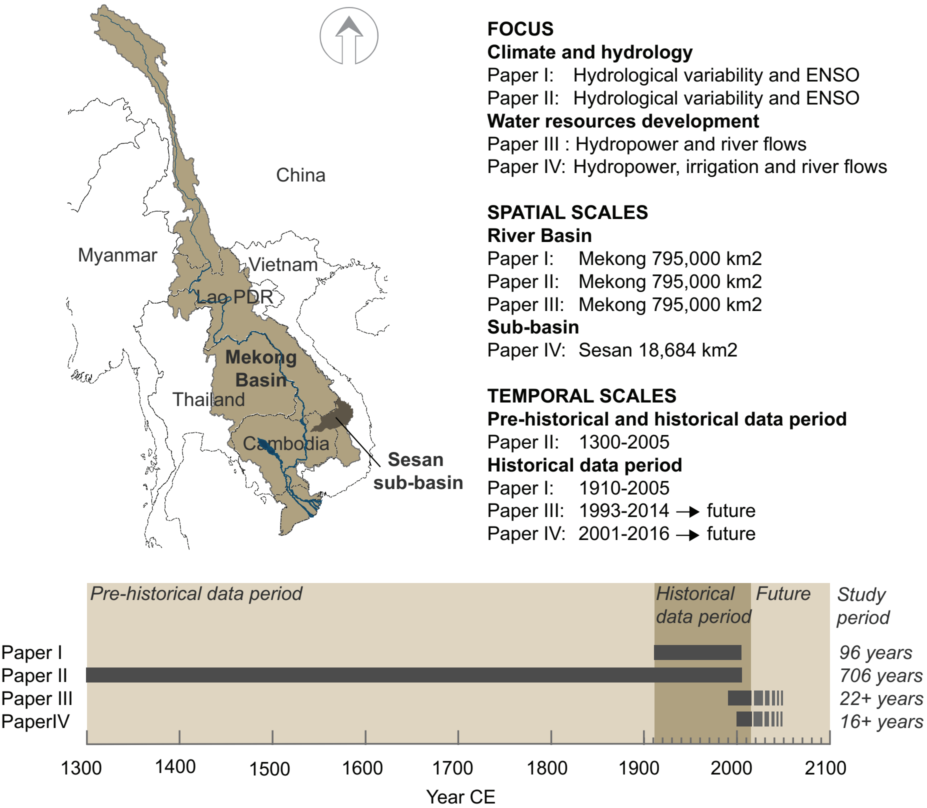
Paper I, *Spatiotemporal influences of El Niño-Southern Oscillation (ENSO) on precipitation and flood pulse in the Mekong River Basin*, investigated the role of climate variability on the Mekong's hydrology. The specific focus was on the influence of the ocean-atmosphere coupled phenomena El Niño - Southern Oscillation (ENSO) on the precipitation and flood pulse of the Mekong over a period of 1981-2005. In addition, Paper I also looked at the changes in the ENSO-hydrology relationship over the period 1910-2005.

Paper II, *Palaeoclimatological perspective on river basin hydrometeorology: case of the Mekong*, continued the investigation of climate-related hydrological variability in Paper I by broadening the temporal scale of the analysis. Paper II developed a basin-wide approach from the Monsoon Asia Drought Atlas (MADA) (Cook et al. 2010) for studying the inter-annual hydrological variability of the Mekong Basin over the period of 1300-2005. ENSO, and its role in the Mekong's long-term hydrological variability, was a central interest of Paper II.

Paper III, *Downstream hydrological impacts of hydropower development in the Upper Mekong Basin*, investigated the downstream river flow impacts of the largest hydropower cascade in the Mekong Basin: the Lancang-Jiang hydropower cascade in the Mekong main stem in China. The river flow impacts were assessed in several locations in the Mekong main stem.

Paper IV, *Model-based assessment of water, food and energy trade-offs in a cascade of multi-purpose reservoirs: Case study of the Sesan tributary of the Mekong River,* investigated the impacts of hydropower development in a more complex setting than Paper III. Paper IV considered multipurpose reservoir operations and related trade-offs in agricultural potential and energy production as well as the downstream flow impacts. The Sesan River basin, a sub-basin of the Mekong, was used as the case study area. The multi-purpose operations that were considered were rice irrigation and hydropower generation.

Papers I, II, III and IV approached the hydrological analyses from different spatial and temporal scales. The investigations of Papers I, II and III had a Mekong Basin wide focus, and Paper IV had a sub-basin scale focus. The temporal scales of Papers I, III and IV were within the period of historical records of Mekong's hydrology, from 1910 onwards, and the temporal scale of Paper II reached back to the year 1300, when there was no direct historical records of hydrology. The findings of Papers III and IV were based on hydrological data from the periods 1990-2008 and 2002-2006 respectively, but also reach into the future as they assessed ongoing and future hydropower development. In the Paper III the first of the assessed hydropower projects was operational in 1993 and the dam cascade is expected to be operational in 2014 and in the Paper IV the first of the assessed hydropower projects was operational in 2001 and the rest are expected to be operational most likely later than 2016 (MRC 2011b). The spatial and temporal scales of Papers I-IV are illustrated in Figure 2.



FOCUS
Climate and hydrology
Paper I: Hydrological variability and ENSO
Paper II: Hydrological variability and ENSO
Water resources development
Paper III : Hydropower and river flows
Paper IV: Hydropower, irrigation and river flows

SPATIAL SCALES
River Basin
Paper I: Mekong 795,000 km2
Paper II: Mekong 795,000 km2
Paper III: Mekong 795,000 km2
Sub-basin
Paper IV: Sesan 18,684 km2

TEMPORAL SCALES
Pre-historical and historical data period
Paper II: 1300-2005
Historical data period
Paper I: 1910-2005
Paper III: 1993-2014 → future
Paper IV: 2001-2016 → future

Figure 2. Summary of the focus and spatial and temporal scales of the dissertation research papers. The Papers I and II focused on climate-induced hydrological variability on the Mekong Basin scale. The Paper III focused on downstream flow impacts of the Lancang-Jiang hydropower cascade in China and estimated the flow impacts as far as Kratie in Cambodia. The Paper IV assessed multi-purpose reservoir development in the Sesan River catchment, a sub-catchment of the Mekong.

2. METHODOLOGY

The methodology of the dissertation is based statistical analysis of hydrological data and mathematical modelling of river basin hydrology and water resources infrastructure. Statistics and mathematical modelling are standard mathematical methods applied in hydrology and water resources research. The statistical methods of the dissertation are mainly based on time series analysis, and the mathematical modelling is based on simulation and optimisation models. In addition, spatial analyses were used in the dissertation, but they had a lesser role. The main principles of these methods and their use in the dissertation are introduced in the following sections.

2.1. Statistics and time series analysis

Hydrological research involves collecting hydrological data, such as rainfall, temperature and river discharge, and then analysing and interpreting the collected data using statistical methods. Statistical methods can roughly be divided into *descriptive statistical methods* and statistical *inference* (Chatfield 2004). Descriptive statistics are used to describe the characteristics of the data. Statistical inference draws further conclusions from the data through estimation of statistical models describing the data and testing statistical hypothesis concerning for example the hydrological phenomena behind the data.

An important form of statistical analysis in hydrological research is *time series analysis*. Time series analysis is a form statistical analysis that aims to extract characteristics of the observed time series (Casella and Berger 2001; Freedman et al. 1991). In time series analysis, a time series is assumed to be produced by some stochastic process (Chatfield 2004). Stochastic processes with time-invariant means, standard deviations and an autocorrelation structure are called stationary, and processes with time-varying means, standard deviations and autocorrelation structure are called non-stationary (Chatfield 2004).

A common feature of the hydrological time series data is that it is often produced by non-stationary stochastic processes, meaning that there can be trends in means, changes in variances and a changing autocorrelation structure in the data (Chatfield 2004; Chen and Grasby 2009; Khaliq et al. 2009). Non-stationarity can cause challenges for the statistical tests and models, but it can also be the key interest in the hydrological research. Understanding the stochastic processes behind the data provides an opportunity to understand and predict the behaviour of the hydrological system from which the data is collected.

In hydrological research, the nature of the stochastic processes, or the behaviour of the hydrological system, can be examined using various methods. The basic parameters of the processes, for example the means and the standard deviations, are often estimated using the method of moments (Dingman 2008). Trends can be analysed by applying the linear regression model (Casella and Berger 2001) or the non-parametric Mann-Kendall trend test (Kendall 1938; Mann 1945). The changes in variance can be examined using Levene's test for the homogeneity of variances (Gastwirth et al. 2009; Levene 1960) in the time domain, and by wavelet analysis (Torrence and Compo 1998) in the frequency domain. Analysis in the time domain refers to analysing the data in respect to time, and in the frequency domain in respect to frequency. The recurring patterns in the data can be examined by the autocorrelation function (Chatfield 2004) in the time domain and by spectral analysis (Chatfield 2004) and wavelet analysis (Torrence and Compo 1998) in the frequency domain. Forecasting involves modelling of the time series by applying methods such as autoregressive-moving average and regression models (Chatfield 2004), artificial neural networks (e.g. Mwale and Gan 2005), ensemble forecasting systems (e.g. Gobena and Gan 2010) and extended stream flow forecasting (e.g. Hamlet and Lettenmaier 1999).

A hydrological system is often known or expected to be affected by an external process, such as climate oscillations (Chen and Grasby 2009). Therefore, the relationship of two time series (such as those describing the hydrological system and the external process) is of great interest in hydrological research. The commonly used time domain methods for examining such relationships include the estimation of the cross-correlations, linear and rank correlations as well as regression models (Casella and Berger 2001; Chatfield 2004). In the frequency domain, the relationship can be examined with spectral coherence analysis (Chatfield 2004) and wavelet coherence analysis (Grinsted et al. 2004).

2.2. Mathematical modelling

Mathematical models are used to simulate various water systems in the field of hydrology. These models can be roughly divided into hydrological models and water resources management models. Hydrological models are used for studying the movement of water between soil, vegetation and atmosphere and hydrological processes of river catchments, whereas the water resources management models are used to study water management of various water infrastructure projects, such as hydropower and irrigation.

The hydrological models can be categorised into stochastic or process-based and lumped or distributed models (see e.g. Carpenter and Georgakakos 2006; Refsgaard and Knudsen 1996). Stochastic models are also called 'black box' models, as they do not consider the complex dynamic processes involved but rather describe the processes using statistic relationships or simplified functions such as regression. Process-based models, also called 'physically-based' models, attempt to describe the processes of a system using mathematical equations. Lumped and distributed models differ in the resolution of the description. For example, lumped models average river catchment characteristics such as spatial rainfall, land cover and soil type distribution, whereas the distributed models attempt to consider the spatial variability of hydrological and catchment characteristics. In distributed models, the computation of processes occurs simultaneously in discretised spatial units considering their individual characteristics as well as the interaction between the units.

The mathematical models used in water resources management and related water infrastructure vary in nature according to their purpose. The models can be divided into simulation and optimisation models or their combinations (Rani and Moreira 2010). The simulation models can be used to simulate a single or multiple network reservoir systems and their various components and operations. These models focus on the simulation technical aspects of the projects, and the hydrological processes of the catchment are often simplified. The development of water resources projects often require separate models for planning and operation (Rani and Moreira 2010). The planning models focus long-term operation policies and can be used for planning the size and characteristics of a project, whereas operational models can be used to re-evaluate and adjust operational policies.

The optimisation models are useful when problems become complex and hard to solve by trial and error. An example of such a case is the goal of a hydropower project to maximise its hydropower production while considering various other objectives, such as the needs of other water users. Several techniques have been developed for solving such complex problems. These include linear, non-linear and dynamic programming, evolutionary computation, fuzzy set theory and artificial neural networks. These methods are reviewed by Labadie (2004) and Rani and Moreira (2010).

The recognition of complexity in human-environment-technology systems and the demands of decision-making and management have resulted in the emergence of integrated modelling approaches (Kelly et al. 2013; Parker et al. 2002). These approaches integrate dimensions of biophysical, social and economic domains, and they attempt to form holistic approaches to support decision-making. The level of integration in these approaches varies, and some are broader in the dimensions they consider.

2.3. Spatial analysis

Spatial analysis refers to analysis where the data is analysed with respect to its geographical characteristics. The spatial data analysis can be based on statistics, but it also considers the geographical attributes of the data. In hydrological research, this may refer to analysing the behaviour of rainfall and temperature data with respect to their location or to understanding the spatial distribution of these hydrological variables. Hydrological data is often based on point measurements, but the behaviour of hydrology between the measurement locations is also a common interest. In addition, hydrological research is often interested in the spatial dependency of data from different locations.

The behaviour of hydrological data can be analysed using Geographical Information Systems (GIS) that help to manage and analyse the data in terms of geographical location. The spatial distribution of the data can be analysed by interpolating point measurements with Thiessen's polygons (Thiessen 1911) and inverse distance weighting and Kriging methods (Dingman 2008). The spatial dependency between data can be analysed using for example correlation and clustering (Romesburg 2004).

In recent decades, the spatial analysis of hydrology has been changed by the emergence of remotely sensed hydrological data. The remotely sensed hydrological data from for example NOAA, MODIS, Landsat, Radarsat and ERS have produced large number regional and global datasets that contain data on various hydrological variables. The advantage of the remotely sensed data is that it provides better spatial coverage and it is often more easily accessible than the land surface based point measurements. Recent research in the Mekong has shown that the use of remote sensing based hydrological data in the modelling of the catchment hydrology resulted in similar accuracy of results as the use of land surface based point measurements (Lauri et al. 2014).

2.4. Methods used in the research papers

Papers I and II, which focused on the climate-related hydrological variability in the Mekong Basin, were based time series analysis of hydrological time series data and they used both descriptive and inferential statistical analyses. Both papers analysed the climatological and hydrological time series data in the time domain and frequency domain using several methods. Papers I and II also examined the correlation or dependence between climatological and hydrological time series, both in the time domain and the frequency domain. In addition, Paper I analysed the spatial behaviour of rainfall using the methods of spatial analysis. The methods used in Papers I and II are listed in Table 1.

Papers III and IV, which focused on analysing the hydropower development in the Mekong, were mainly based on mathematical modelling. In both papers, modelling approaches were developed where two or more models provide data to the other(s). Both papers modelled catchment hydrology and hydropower projects. In addition, Paper IV also used modelling tools to estimate land suitability and the crop-water requirements for irrigated rice. The developed modelling approaches were flexible, as they allowed the user to relatively freely define the aspects of the modelled water resources development. The modelling applications also considered complex operations such as optimisation of power production and cascade and multipurpose operations of hydropower projects on the river catchment scale. The methods used in Papers III and IV are also listed in Table 1.

Table 1. Methods and tools used in the dissertation research Papers I-IV.

Paper	Method	Tools
Paper I: Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong	Statistical timeseries and spatial analysis	Linear correlation Cross-correlation Regression model Spectral analysis Inverse distance weighting method Clustering
Paper II: Palaeo-climatological perspective on river basin hydrometeorology: case of the Mekong	Statistical timeseries analysis	Linear correlation Local regression (LOESS) Levene's test of homegeneity of variances Wavelet analysis
Paper III: Downstream hydrological impacts of hydropower development in the Upper Mekong Basin	Mathematical modelling	Distributed hydrological model VMod/IWRM Dynamic programming tool CSUDP
Paper IV: Model-based assessment of water, food and energy trade-offs in a cascade of multi-purpose reservoirs – Case study from transboundary Sesan River	Mathematical modelling	Distributed hydrological model VMod/IWRM Land use suitability evaluation tool LUSET Crop water requirement model CROPWAT Dynamic programming tool CSUDP

2.5. Data used in the research Papers

The analysis of ENSO's influence on the Mekong's hydrology in Paper I was based on daily precipitation observations from 149 meteorological stations (MRC 2011b; NCDC 2011) and daily discharge data from six Mekong mainstream gauging stations (MRC 2011b). The precipitation data covered the period of 1981-2005 and the discharge the period of 1910-2008. For describing ENSO patterns a monthly ENSO index was used (Meyers et al. 2007; Ummenhofer et al. 2009).

The palaeoclimatological analysis of Mekong's hydrological variability was based on palaeo proxy data from Monsoon Asia Drought Atlas (MADA) (Cook et al. 2010) and discharge data from Mekong mainstream gauging station at Stung Treng in Cambodia (MRC 2011b). MADA is a gridded Palmer Drought Severity Index (PDSI) (2.5^{o} x 2.5^{o} resolution) describing summer (JJA) monsoon conditions over the monsoon Asia for the time period of 1300-2005. MADA has been constructed using global gridded observation based PDSI dataset (Dai et al. 2004) and tree ring records from more than 300 sites in Asia. The discharge data, which was used for the validation of the use of MADA in the Mekong, covered the time period of 1910-2005. In addition, for describing ENSO patterns a monthly extended Multivariate ENSO Index was used (Wolter and Timlin 2011).

The assessment of hydropower development in Papers III and IV were partially based on same data sets. The construction of the hydrological models for the investigated river basins involved the use of basin boundary and river network data (MRC 2011b), digital elevation model (DEM) (Jarvis and Reuter 2008) and soil type (FAO 2007) and land use data (GLC 2000 2003). The hydrological models were forced by measured daily precipitation and temperature data and calibrated against measured daily discharge data (MRC 2011b). The temperature data for hydrological model in Paper IV was also supplement by re-analysis data (NOAA 2013).

The hydropower simulations in Papers III and IV were based DEM estimations of the reservoir shapes and dam and hydropower production characteristics of each hydropower project (MRC 2011b). The hydropower simulations were driven by simulated discharge data extracted from the hydrological models.

The land suitability assessment in Paper IV used terrain, soil type and soil hydrological properties data from Mekong River Commissions Watershed Classification Project (WSCP); soil properties data from soil survey data of Sesan Catchment in Kontum Province, provided by the Western Highlands Agro-Forestry Sciences and Technical Institute; precipitation and temperature data from the hydrological model; and crop requirement data from Sys et al. (1993), which was supplemented with local expert knowledge.

The crop water requirement assessment in Paper IV used precipitation and temperature data from the hydrological model. The soil type for irrigation was simplified and assumed as loam and sandy loam Upper and Lower Sesan catchments. The cropping and irrigation patterns were assumed according to local practices: for wet season medium variety with the 125 day cropping period with supplementary irrigation and for dry season earlier variety with the 105 day cropping period with 7-day rotation of 100 mm of standing water.

3. FINDINGS: CLIMATE VARIABILITY, HYDROPOWER AND HYDROLOGY

This section presents the main hydrological and water resources management findings from Papers I-IV. The main findings in Papers I and II are presented in Section 3.1. They provide views on the climate induced hydrological variability in the Mekong. Section 3.2 presents the main findings from Papers III and IV, providing a view on how human actions (namely hydropower and irrigation development) are affecting the hydrology of the Mekong. Section 3.3 then draws from Papers I, II, III and IV and analyses the potential cumulative hydrological changes resulting from climate variability and hydropower development.

3.1. Climate-related hydrological variability

The statistical analyses of precipitation discharge and ENSO data in Paper I revealed that the Mekong's hydrology is strongly influenced by ENSO and that the majority of the recent droughts and floods occurred in conjunction with ENSO events. It was found that during the El Niño (La Niña) events, the basin-wide annual rainfall anomaly was on average –5.3% (+6.6%) (Figure 3). The spatial analysis of precipitation revealed that the influence of ENSO on precipitation was more pronounced in the southern parts of the basin. The statistical analysis of discharge and ENSO data showed that influence of ENSO was also significant on the main stem of the Mekong (Figure 4). In the lower reaches of the Mekong in Stung Treng Cambodia (see location in Figure 2), the annual flow volumes decreased on average by 19.9% during El Niño and increased by 13.2% during La Niña. The lowest (highest) flows of the high flow period were also associated with El Niño (La Niña) events. In addition, ENSO modulated the timing of the annual flood pulse: the start of the flood period was delayed (advanced) and the flood period was shorter (longer) during El Niño (La Niña) events. These ENSO influences were detected during the second year (the decaying year) of the ENSO event. The findings also suggest the potential to forecast droughts and flood risks resulting from ENSO (see also Singhrattna et al. 2005). The characteristics of the flood pulse can also be considered as indicators for the timing and intensity of the monsoon rains.

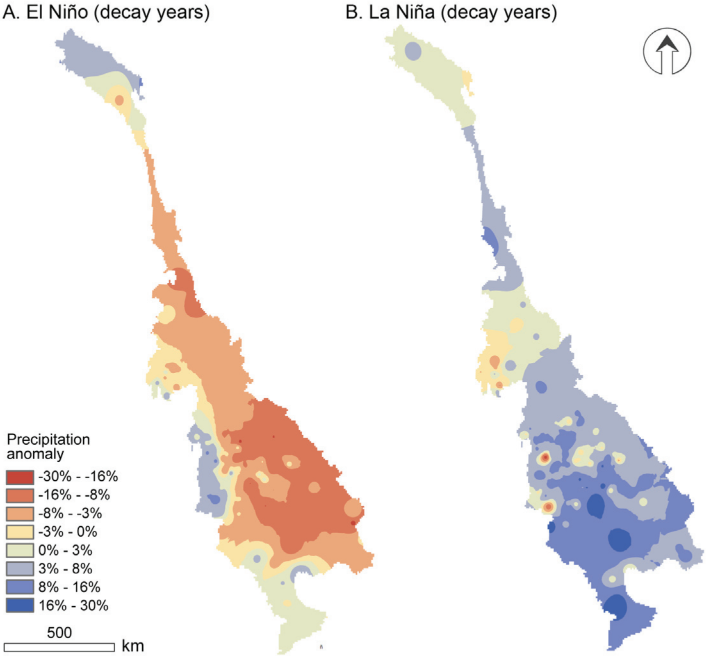


Figure 3. Average annual rainfall anomalies in the Mekong Basin during the decay years of (A) El Niño and (B) La Niña over the period 1981-2005. El Niño and La Niña events generally start to develop in June-August, peak in December-April, and decay in the following year in May-April. The influence of ENSO events in the Mekong was found to be strongest in the years when the events decayed. Figure adapted from Paper I.

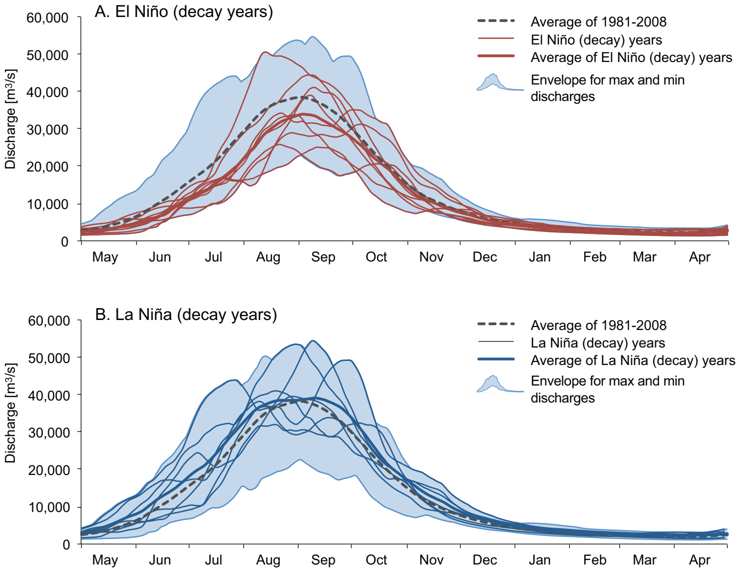


Figure 4. Flood pulse anomalies at the Mekong main stem in Stung Treng in Cambodia during the decay years of (A) El Niño and (B) La Niña over the period 1981-2005. El Niño and La Niña events generally start to develop in June-August, peak in December-April, and decay in the following year in April-May. The influence of ENSO events in the Mekong was found to be strongest in the years when the events decayed. Figure adapted from Paper I.

The statistical analyses of discharge and hydrological palaeo proxy data, both in time and frequency domain, in Paper II revealed that the Mekong's hydrology has strong non-stationary features. The hydrological conditions were found to vary between wetter and drier periods of multi-annual and decadal lengths (Figure 5A), of which the most recent dry period in the second half of the 20th century was one of the driest. In addition, the variance analysis of palaeo proxy data showed that the most significant changes in the inter-annual variability occurred in the second half of the 20th century when the inter-annual variability increased to levels that have not been experienced for at least the past 700 years (Figure 5B). The increased inter-annual variability has resulted in the increased occurrence of very dry and very wet years. For example, the most recent decades experienced many of the driest years (e.g. 1991, 1992, 1993, 1998 and 2005) and wettest years (e.g. 1999, 2000 and 2001) in the 706-year study period. These findings in general suggest that there is no stable hydrological baseline with statistically constant mean and standard deviations. Instead, the hydrological baseline could be considered as being under constant change.

The frequency domain analyses of discharge, palaeo proxy and ENSO data in Paper II revealed that the increase in inter-annual variability during the second half of the 20th century occurred largely in the wavelengths of 2 to 7 years that are commonly associated with ENSO (Sarachik and Cane 2010). The correlation analyses in frequency and in time domain showed that the correlation between ENSO and discharge and palaeo proxy data strengthened during the post 1980 period. This indicates that ENSO was one of the factors behind the increased inter-annual hydrological variability in the Mekong during the latter half of the 20th century. Furthermore, it was found that the ENSO signal became stronger in the Mekong's hydrology from the 1970s onwards.

Recent research has found that the activity of ENSO has increased during the past decades (Cobb et al. 2013; D'Arrigo et al. 2005; McGregor et al. 2013; Yu et al. 2012) and the increased ENSO activity is a result of global warming (Cai et al. 2014; Li et al. 2013). Thus, the Mekong has already experienced the effects of global warming through ENSO, at least in the form of increased inter-annual hydrological variability.

It is also important to recognise that ENSO is not the only source of hydrological variability in the Mekong, although the majority of the severe flood and drought years were associated with ENSO events. The Paper I showed that almost 50% of the inter-annual variability could be explained by ENSO and the rest was left unexplained. In addition, individual floods can be the result of tropical cyclones or other weather events. Recent research has confirmed that the Mekong's hydrology is also strongly related to the western north Pacific monsoon (Delgado et al. 2012), and tropical cyclones and the Indian Ocean dipole (Darby et al. 2013). In addition, the Madden-Julian Oscillation, Quasi-Biennial Oscillation and decadal cycles (Chen and Chappell 2009) such as the Pacific Decadal Oscillation (Delgado et al. 2012) are known to affect the hydrological conditions in the tropics of Southeast Asia but their influence on the Mekong has not been scientifically well-examined.

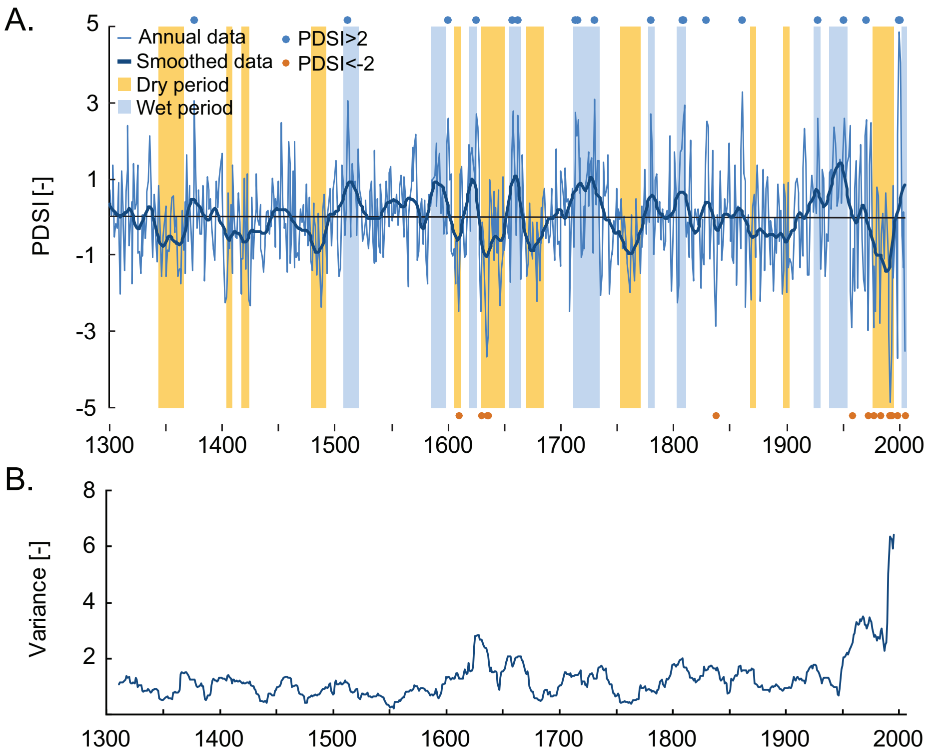


Figure 5. The basin-wide Palmer Drought Severity Index of summer monsoon months (JJA) for Mekong Basin ($PDSI_M$): over the period 1300-2005: (A) The annual values (thin blue line), LOESS smoothed values (thick blue line, LOESS span 21 years), dry and wet periods (yellow and blue shadings), years with $PDSI_M$ values above 2 and below –2 (blue dots and yellow dots); and (B) Moving window variance of $PDSI_M$ (window size 21 years). Figure adapted from Paper II. The $PDSI_M$ was derived from the Monsoon Asia Drought Atlas (MADA) (Cook et al. 2010).

3.2. Hydropower and irrigation development

The Paper III assessed the downstream flow impacts of the Lancang-Jiang hydropower cascade in China, which is the largest hydropower cascade in the Mekong Basin. The cascade will consist of six large dams with a total power production capacity of 14,800 MW and a reservoir regulating capacity of 23 km^3. It is due to be fully operational in the year 2014 (MRC 2011b). The regulating capacity corresponds to 28% of the annual flow at Chiang Saen (see location in Figure 1), at the border of Thailand and China, and 5% of the annual flow of the whole Mekong. The location of the Lancang-Jiang hydropower cascade is shown in Figure 1 and the technical characteristics in Table 2.

The Paper IV focused on the combined influences of hydropower operations and cascade of multipurpose reservoirs on river flows. The Paper IV used the Sesan River catchment with seven existing and four planned hydropower dams (Figure 8) as a case study. The total regulating capacity of these eleven reservoirs in the Sesan was 3 km^3, corresponding to 15% of the annual flow of the Sesan River. All eleven dams were simulated, with seven of them facilitating a total irrigation of 23,348 ha of dry and wet season rice. The location of each hydropower projects in Sesan Catchment is shown in

Figure 8 and their technical characteristics in Table 3. The main findings of these two Papers III and IV are presented in the following.

Table 2. Characteristics of the Lancang-Jiang hydropower cascade in Mekong Basin in China (see location in Figure 1). Data from (ADB 2004).

	Commission year	Installed capacity [MW]	Active storage [km^3]	Dam height [m]	Announced hydropower generation [GWh]
Gonguoqia	2011*	750	0.12	130	4,670
Xiaowan	2012*	4,200	9.9	300	18,540
Manwan	1993*	1,500	0.26	126	7,870
Dachaoshan	2003*	1,350	0.37	110	7,090
Nuozhadu	2014*	5,500	12.3	254	22,670
Jinghong	2013*	1,500	0.25	118	8,470
TOTAL		14,800	23.19		69,310

The simulation of the Lancang-Jiang hydropower cascade with optimisation model revealed that the cascade will have considerable impacts on the Mekong's flows, which were observable as far downstream as Kratie in Cambodia (see location in Figure 1). The amplitude of the annual flood pulse was reduced and the dry season flows increased. At the main assessment location, Chiang Saen, the dry season flows (Dec-May) increased 34-155% and wet season flows (Jul-Sep) decreased 29-36% (Figure 6). The variability in dry season flows was also increased considerably (Figure 6). The flow changes resulted in reduced amplitude and duration of the annual flood pulse. In Kratie (see location in Figure 1), the dry season flow increases of 49% (Mar) were observed, which corresponds approximately to a 1.1 m rise in water level (Figure 7).

The variations in climate were also found to affect the flow regulation of the Lancang-Jiang cascade. During the weaker monsoon years, the reduction in wet season flows was higher, as the reservoirs stored a larger proportion of the available wet season flow, compared to the average monsoon year. Consequently, the dry season flows were also affected by the monsoon intensity. During the weak monsoon years, the reservoirs released less water in the dry season than during the strong monsoon years. In general, the flow variations during the dry season were increased by the Lancang-Jiang cascade compared to variations in the natural non-regulated flow dry season regime (Figure 6). The combined influences of climate variability and hydropower development have already raised discussion in the region. During the dry season in 2010, parts of the Mekong experienced exceptionally low water levels and the Chinese dams were blamed for this (Stone 2010), but the situation was at least partially caused by low rainfall and the early end of the wet season (Paper III; Qiu 2010; Stone 2010).

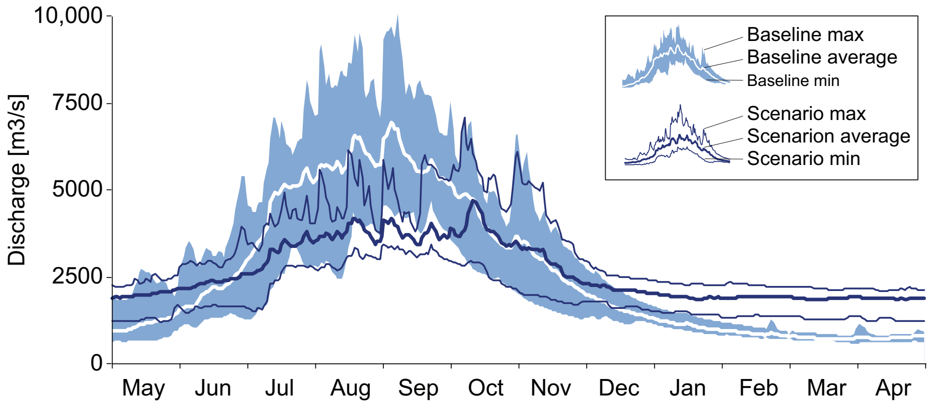


Figure 6. Estimated downstream flow impacts of the Lancang-Jiang hydropower cascade at Chiang Saen (see location in Figure 1) with all six dams operational. Figure adopted from Paper III.

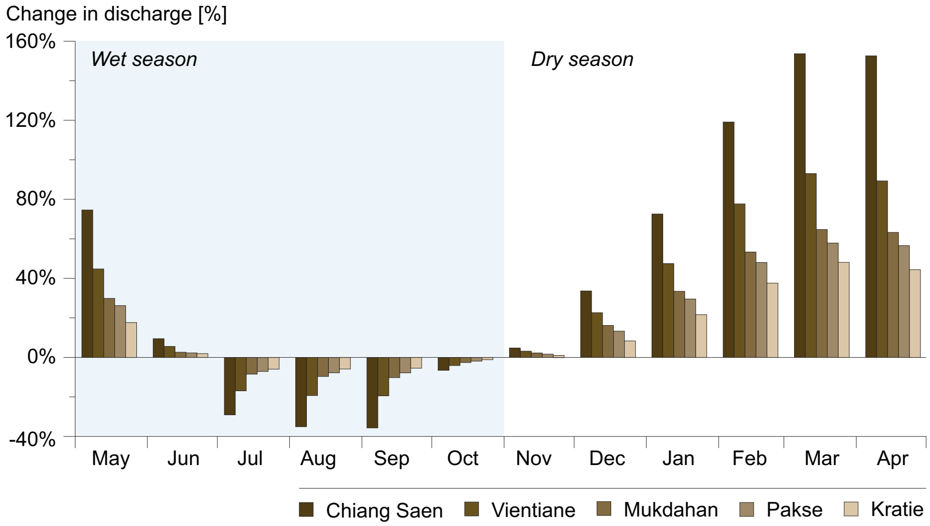


Figure 7. Estimated monthly downstream flow impacts of the six dams of the Lancang-Jiang hydropower cascade at five locations in the Mekong main stem: Chiang Saen, Vientiane, Mukdahan, Pakse and Kratie (see locations in Figure 1). Figure adopted from Paper III.

The assessment of hydropower development in the Sesan River catchment (Figure 8) through the five-stage modelling approach developed in Paper IV suggested similar river flow changes as in the case of the Lancang-Jiang cascade. At the outlet of the Sesan River the dry season flows increased by 2-201% (Dec-Jun), and the wet season flow decreased by 4-19% (Jul-Oct) (Figure 9A). The inclusion of 23,348 ha of irrigated rice in the hydropower simulations revealed additional impacts on the river flows, but the impacts were relatively small compared to the impacts of hydropower operation on the natural flow regimes. At the outlet of the Sesan River the dry season flows increased by 1-176% and the wet season flows decreased by 4-20% (Figure 9A). The total water consumption of the 23,348 ha of dry and wet season irrigation was 0.39-0.43 km^3, corresponding to an annual water loss of 1.9-2.1% of the flow of the Sesan. Thus the combined impact of hydropower operations and irrigation resulted mainly in slightly reduced dry season flows compared to the flow impacts of only the hydropower operations.

The simulated flow impacts of irrigation were found, however, to be more complicated than the first assessment results suggested. The flow impacts were also simulated and assessed in a situation where the hydropower reservoirs were not in place but the irrigation water abstraction for 28,348 ha would occur directly from the river. The results showed that this would result in considerable flow depletion during the dry season (Figure 9B). The flows were reduced around 32% (in February), and the most severe flow depletion occurred in early May, when the river flow was reduced by 70% (Figure 9B). It is important to also acknowledge that the assessment did not consider existing irrigation in the Sesan catchment. The upper part of the Sesan catchment in Vietnam has at least 28,000 ha of irrigated rice (GSO 2013) and may also have other irrigated crops. If the existing irrigation would have been included in the case study assessment, the river flows would have been affected to a greater degree. However, the comparison of the irrigation water abstraction against the natural non-regulated flow regime revealed that dry season river flows will be easily depleted due to agricultural water consumption. In addition, Paper IV revealed that water consumption may be less easily recognisable in river flows due to the large flow impacts of hydropower projects.

The model-based assessment of multipurpose dams through the Sesan case study also revealed other challenges and trade-offs. The reservoirs and agricultural expansion would affect a land area of 1,315 km^2, which is equivalent to 7% of the Sesan catchment. This would negatively impact protected areas, forests and agriculturally valuable land. The irrigation was also found to reduce the annual hydropower generation of nine projects by 0.6-3.4% (Table 3). In addition, the impacts of multipurpose reservoir development were transboundary, which emphasises the need for co-operation between Vietnam and Cambodia.

The five-stage modelling approach used in Paper IV could not consider social or ecological aspects of the multipurpose reservoir development, but it is likely that the local livelihoods and economic activities would also be impacted, as the previous studies from Sesan have shown (Wyatt and Baird 2007). The Sesan is also known to be rich in fish biodiversity (Baran et al. 2011; Poulsen et al. 2004), which would be negatively affected by hydropower development (Baran and Myschowoda 2009; Ziv et al. 2012). Thus, based on Papers III and IV, it is concluded that the assessment of river flow impacts can be relatively straightforward, but the flow impacts form only one component of the trade-offs that concern ecology, local livelihoods and broader societal needs.

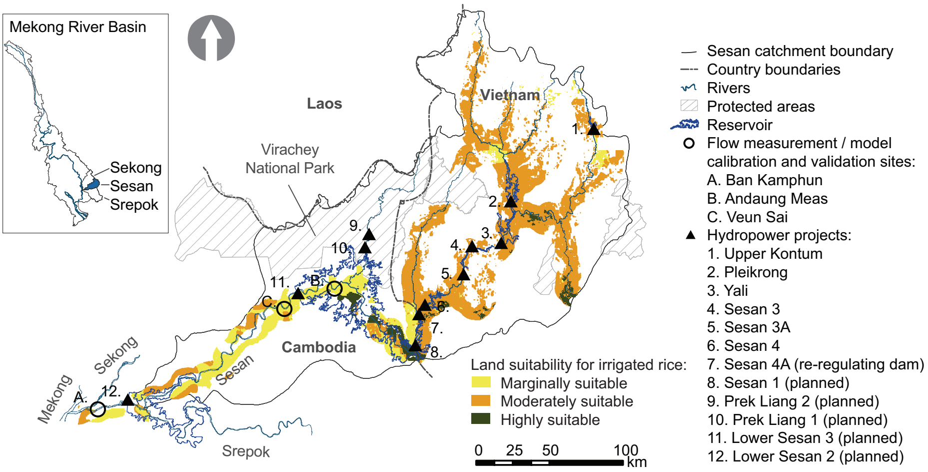


Figure 8. Map of the Sesan River Basin showing the existing and planned large hydropower projects (>15 m) considered in Paper IV. The map also shows the areas defined as suitable for irrigated rice along the main rivers. Figure from Paper IV.

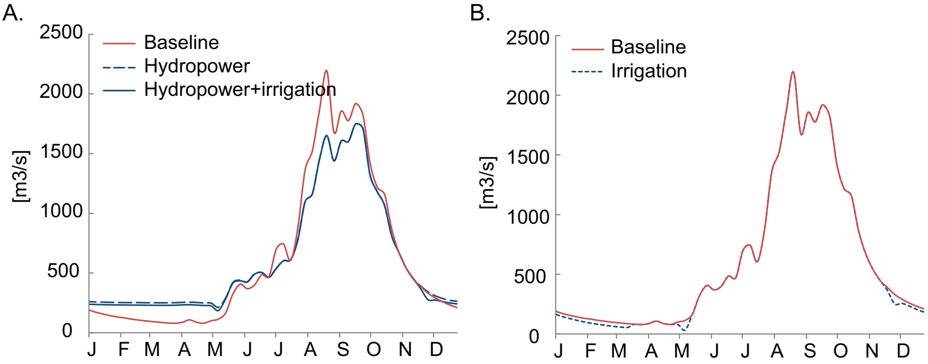


Figure 9. The estimated average river flow impacts of (A) hydropower operations and irrigation, and (B) irrigation without hydropower operations at the outlet of the Sesan River (Figure 8). The estimations consider operation of eleven hydropower projects and irrigation of 28,348 ha from seven reservoirs. The data in the figure is on a weekly time scale. Figure adapted from Paper IV.

Table 3. Characteristics of the hydropower projects in Sesan Catchment, the simulated irrigated areas and corresponding hydropower production losses. The location of hydropower projects are shown in Figure 8. Table adapted from Paper IV.

	Commission year	Installed capacity [MW]	Active storage [Mm3]	Reservoir area [km2]	Announced hydropower generation [GWh]	Baseline annual hydropower generation [GWh]	Irrigation scenario [ha]	Annual hydropower loss [GWh (%)]
Upper Kontum	2011	250	122.7	7.4	1,056	1,057	600	20.3 (-1.9%)
Pleikrong	2008	100	948	53.3	417	497	2,817	7.1 (-1.4%)
Yali	2001	720	779	65	3,659	3,850	0	24.9 (-0.6%)
Sesan 3	2006	260	3.8	3.4	1,225	1,228	0	7.4 (-0.6%)
Sesan 3A	2007	96	4	8.5	475	454	6,490	7.8 (-1.7%)
Sesan 4	2009	360	264.2	58.4	1,420	1,478	3,474	30 (-2%)
Sesan 4A*	2008	-	7.5	1.7	-	-	5,091	-
Sesan 1	NA	90	3.4	10.6	480	641	0	20.6 (-3.2%)
Prek Liang 2**	NA	25	180	11.9	-186	-238	-	-
Prek Liang 1**	NA	35	110	7	-189	-314	-	-
Lower Sesan 3	NA	243	323	4140	1,977	1,634	7,843	55.7 (-3.4%)
Lower Sesan 2	2016	480	379.4	394	2,312	2,218	2,033	28.7 (-1.3%)
TOTAL		2,659	3,125	4,761	13,396	13,057	28,348	202.5 (-1.6%)

* Sesan 4A is a re-regulating dam for Sesan 4 and does not have a power plant.

** Prek Liang 2 and 1 were excluded from the irrigation assessment as they are located inside a protected area. They were simulated to cover their river flow impacts but excluded from the energy assessment.

3.3. Potential cumulative impacts on river flows

Papers I, II, III and IV presented hydrological changes resulting from climate variability and direct human actions of hydropower and irrigation development. These changes, when occurring concurrently, may result in unexpected cumulative impacts. In this section, the findings of the research Papers are jointly discussed from this perspective and summarised in Table 4. Four cumulative impacts resulting from ENSO and hydropower and irrigation development were identified and are presented in the following. The hydrological concepts used in the discussion are introduced in Figure 10.

> *Dry season river flows*: The hydropower operations increased the dry season flows and the irrigation reduced them (Papers III and IV). The impacts of hydropower development were, however, considerably larger than those of irrigation (Paper IV). The hydropower operations during the dry season were found to be affected by variations in wet season flows. After an above (below) average wet season, the dry season flows were higher (lower) than the average dry season flows under hydropower operations (Paper III). It was also found that ENSO affects inter-annual flow variability and peak flows (Paper I). Thus the cumulative impact of hydropower development and ENSO can be an increase in inter-annual flow variability in the dry season flows. For example, after an El Niño (La Niña) year, the dry season may experience lower (higher) water levels compared to average dry season flows under hydropower operation.
>
> *Early wet season river flows*: The hydropower operations delayed the start of the high flow period (Paper III). El Niño events also delayed the start of the high flow period, but the La Niña events advanced the start of the high flow period (Paper I). Thus, the cumulative impact can be a considerably delayed high flow period during El Niño events.

Wet season river flows: The hydropower development was found to reduce the wet season flows and the duration of the high flow period. El Niño events were associated with lower peak flows and shorter high flow periods, while La Niña events were associated with higher peak flows and longer high flow periods (Paper I). Thus, the cumulative impact of hydropower and ENSO can be a considerably reduced wet season flows and shorter high flow periods (longer low flow periods) during El Niño events. In addition, if the long-term climate-induced hydrological variability between wetter and drier periods (Paper II) is considered together with the impacts of hydropower, the cumulative impact can be an overall decrease in wet season flows during the periods that are drier than average. The long-term climate-induced hydrological variability may also result in unexpectedly high flows (with regard to the design flows of the hydropower projects) if the design flows are based on flows from drier periods.

Flood pulse amplitude: The hydropower development was found to reduce the amplitude of the annual flood pulse (Paper III), and ENSO affected the peak flows by reducing them during El Niño events and by increasing them during La Niña events (Paper I). Thus, the hydropower development and ENSO can result in cumulative impacts where the flood pulse amplitude is considerably reduced during El Niño events. Here again, as in the case of the wet season flows, the cumulative impact of long-term climate-induced hydrological variability (Paper III) and hydropower operation, the cumulative impact can be an overall decrease in flood pulse magnitude during the periods that are drier than average.

A few remarks are warranted here. The cumulative impacts presented above are based on findings from limited data and limited methodologies and should be therefore considered as possible impacts and subject to uncertainties. For example, the estimates on cumulative impacts depend on uncertainties in the dam operations, which the used modelling approaches could not address adequately, and in the occurrence intervals and intensities of ENSO events. In addition, the global warming will also bring uncertainties as it is expected to have an impact on Mekong's climate, but the direction and magnitude of the impacts on the flow regimes are uncertain (Lauri et al. 2012). It is also important to acknowledge that the above-mentioned hydrological changes do not represent a comprehensive analysis of all the potential hydrological variations and cumulative impacts in the Mekong. Therefore, in reality the cumulative impacts can be more elusive and uncertain than the above analysis suggests. It is also worth mentioning that the concept of peak flood in the above discussion and in Table 4 refers to peak flood calculated from a 7-day average flow.

Table 4. Summary of the estimated hydrological changes from ENSO, hydropower operations and irrigation water abstraction. See Figure 10 for a description of the variables.

	ENSO	El Niño	La Niña	Hydropower	Irrigation
Rainfall					
Annual rainfall		↓	↑		
Inter-annual rainfall variability	↑				
River flow					
Annual flow		↓	↑	—	↓
Inter-annual flow variability	↑				
Dry season flow				↑	↓
Dry season flow variability				↑	
Wet season flow		↓	↑	↓	—
Wet season flow variability				↓	
High flow period start		→	←	→	
High flow period start variability	↑				
High flow period end		—	—	←	
High flow period variability				↓	
High flow period duration		↓	↑	↓	
Annual peak flow		↓	↑		
Annual peak flow timing				→	
Flood pulse amplitude				↓	

↑ = Increase
↓ = Decrease
← = Advance
→ = Delay
— = No detected change
Empty = Not assessed

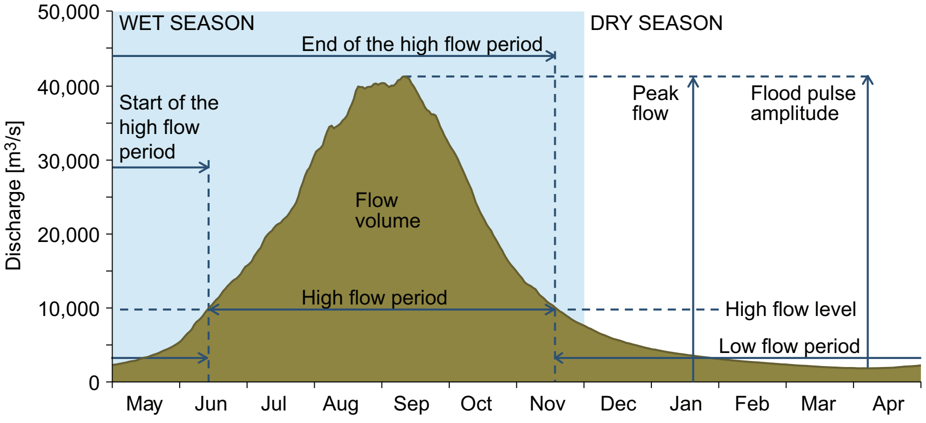


Figure 10. Annual average flow regime, i.e. the flood pulse, of the Mekong at Stung Treng, Cambodia. The figure also shows specific characteristics of the flow regime used in the discussion of this dissertation. Wet and dry season definition from MRC (2005). Figure adapted from Paper I.

4. DISCUSSION: REFLECTIONS ON THE HYDROLOGICAL KNOWLEDGE PRODUCTION

This section addresses the fourth research question of this dissertation: *What implications disciplinarity and discipline specific standard methods (in this case statistics and mathematical models) have on the production and use of hydrological knowledge?* This is done by discussing the methods used as the basis of the methodology of the dissertation and the experiences from the disciplinary approaches in the Mekong. The first sub-section (Section 4.1) discusses the methods, statistics and mathematical models, and the second sub-section (Section 4.2) discusses the disciplinarity and more psychological aspects related to knowledge production. The third and last sub-section (Section 4.3) provides some future directions for hydrological research on the basis of the research findings and a discussion on the use of methods and disciplinary aspects. The discussion in this section focuses only on the aspects that are important in the context of the dissertation and it is a comprehensive analysis of disciplinary research.

4.1. Methodological considerations

In this dissertation, descriptive statistics were mainly used to understand past hydrological conditions, while the statistical models were used for testing hypotheses and predicting future hydrological changes. The mathematical models were found to be particularly useful in providing a tool for testing hypotheses without disturbing the real world. However, several aspects were found that needed to be recognised in the appropriate use statistical and modelling methods. The failure to recognise these aspects may result in inadequate or misleading research findings.

4.1.1. Statistics

The statistical methods as such are relatively straightforward to apply on data by using readymade software, but the correct use of the methods was found to be entirely another issue. For example, statistical methods require many assumptions concerning the data (such as the distribution, correlations and stationarity of the data to hold), whilst the hydrological data may not always satisfy these assumptions (Chen and Grasby 2009; Clarke 2010; Khaliq et al. 2009). For example, Paper II showed that the hydrology of the Mekong is highly non-stationary and correlated. Therefore, adequate emphasis is needed to understand the nature of the data and the assumptions of the methods.

The general fact in statistics – that statistical inference between two datasets does not necessitate physical causality between the datasets – was well recognised in the dissertation. This fact can never be stressed enough, as it is easy to neglect, which may result in substantial errors. For example, in Paper I, which investigated the relationship between ENSO and Mekong's hydrology, great rigour was needed to adequately understand the behaviour of ENSO as well the behaviour of IOD. These two phenomena affect Mekong's hydrology (Darby et al. 2013) and are thought to be independent, but they often co-vary (Meyers et al. 2007). Therefore, their combined influence could have complicated the statistical analysis of the ENSO-hydrology relationship in the Mekong, as discussed also by Darby et al. (2013). This challenging problem was examined and adequately solved through a literature survey and statistical analysis of both ENSO and IOD, and it was found that there was no significant influence from IOD during the study period. However, the influence of IOD on the results could not be fully ruled out. Thus, Paper I presents an example on the importance to understand the causality behind the statistical correlations of two or more phenomena.

Another important aspect in the use of statistics is the inductive nature of statistical inference. Induction in statistics means that a limited set of data is used to draw broader generalisations. For example, in hydrology, a certain time length of time series data can be used to extract information on the average conditions and on the probability and magnitude of extreme events. The Paper II, however, showed at least in two examples that such an approach has its uncertainties. Firstly, the Mekong's hydrology has varied naturally between wetter and drier periods, and this has implications on the estimations of averages as well as on the trend analyses (see also Chen and Grasby 2009). Secondly, recent decades have experienced the wettest years in recorded history since 1910 and potentially over the past 700 years (see also Delgado et al. 2010; Delgado et al. 2012; MRC 2011a).

The above examples show how past historical data may be a poor predictor of future events. This issue has also been discussed by Nassim (2007; 2008). He argues that probabilistic methods for risk estimation based on historical data have resulted in serious and harmful consequences. He defines a danger area where statistics is a poor tool for risk assessments. In this area, the consequences of an event are large and complex, and at the same time, the probability distribution of the data is heavy-tailed or unknown. Thus, the generalisations drawn from statistical analyses require broad consideration on the limitations of the methods as well as expert judgement.

4.1.2. Mathematical models

The reality is a complex network of interactions and feedback, and this poses a major challenge for mathematical models. In order to make the reality easier to grasp, it is generally described with concepts. These concepts are then used as the basis for model construction. However, the concepts are reductionist and have various challenges, such as oversimplification (Callagher and Appenzeller 1999). Thus the models based on reductionist concepts also make the models imperfect tools for describing real-world phenomena (see also Sterman 2002). During the dissertation research, the main limitations of the models were found to originate from the reductionist basis of the models and more concretely from the model boundaries and simplifications of the modelled phenomena.

Model boundaries define the aspects that the model includes and excludes. For example, the model boundaries in the dissertation Papers III and IV excluded the ecological, economic and social domains, and focused more on the hydrological and technological aspects. The connection of hydrological and water resources management models to these broader domains has been generally weak in the Mekong (Johnston and Kummu 2012) with few exceptions (Arias et al. 2014a; Holtgrieve et al. 2013; Lamberts and Koponen 2008). The Papers III and IV also did not consider all existing water resources infrastructure in the research areas (e.g. dams upstream of the Lancang-Jiang cascade and existing water use in the Sesan), but focused only on selected infrastructure projects. Thus, the model boundaries have direct implications for the results and on the conclusions drawn from the models. Therefore, the boundary conditions and their implications for the results should be recognised and openly reported.

The problem of narrow model boundaries is tackled by developing integrated modelling approaches, which more broadly integrate various biophysical and human aspects (see e.g. Liu et al. 2008; Rotmans and van Asselt 2001). This inevitably brings solutions to some of the problems that narrow model boundaries might cause, but so far, integrated approaches are quite far from addressing the complexity of human-technology-environment systems (Pahl-Wostl 2007).

The necessity of simplification in models inevitably results in the use of a simplistic description of real-world phenomena. Simplification may occur due to difficulties in describing mathematically highly complex phenomena, from the lack of data or from the lack of modelling resources such as time and computational power. Simplification may, however, have implications on model results and conclusions drawn from them. For example, the two modelling Papers (III and IV) of this dissertation simulated hydropower operation on a weekly time scale due to lack of information on detailed operational goals. This simplification led to the neglect of operation and events on a shorter temporal scale, including hourly and daily water level fluctuations and extreme events such as high floods. The outcome is that the model results suggest stable river flows and a lack of high floods. In reality, this is not the case. The hydropower projects have caused rapid water level fluctuations with harmful impacts (Wyatt and Baird 2007) and have not been able to reduce major floods (Ward et al. 2013). The modelling efforts on the impact assessment of hydropower development in the Mekong have suffered from this problem, which have resulted in an inadequate focus on the impacts of short-term events. Here again, as in the case of the model boundaries, the simplification in modelling works, and their implications for results should be recognised and openly reported. It is also important to recognise that simplicity as such is not always a negative quality. For example, according to the principle of parsimony, simple but adequate models are in many cases the most efficient and accurate ones (Gauch 2012).

The use of models has inductive and deductive elements that further have implications on the interpretation and reliability of the information that the models produce. The inductive element refers here to the common practice that the model results from a certain simulation period are often generalised and considered applicable outside of the simulation period. However, as Paper I and Paper II of this dissertation showed that the Mekong's hydrology varies between wetter and drier periods with an increased occurrence of very dry and wet years, it is obvious that the model results apply only for the hydrological conditions of the simulation period. Therefore, it is highly important to recognise the nature of the hydrological baseline used in the simulations and its implications on the results and their generalisation.

The deductive element in the use of models refers here to the fact that modelling involves various assumptions on some of the variables of the modelled process made by the modeller. These assumptions, or premises, become part of the logic of the modelling process on which the results are based. The general premises of the logic behind the model results are: the driving data is correct and adequate, the model is correct and adequate, and the assumptions done by the modeller are correct or adequate. Whether such premises are true determines the validity and accuracy of the modelling results. The first two premises can be verified by technical means, but the last premise often requires methodological consideration and rigour from the modeller or from other experts. For example, the dissertation Paper III and Paper IV, involving hydropower simulations, made an assumption that the goal of the hydropower projects was to maximise annual energy production. Such an assumption inevitably affects the accuracy and validity of the modelling results. Therefore, the modelling works should openly report the important assumptions as well as their potential implications for the results.

In addition, due to the reductionist nature of the models, a concern is raised here on the potential of models to shape our views of reality and problems we attempt to solve. The model-based interpretation of reality may result in thinking that the world consists of discrete entities and inter-connections that are easily identifiable and manageable. Such views may lead to ignorance towards the complexity of nature and its feedback mechanisms and may make our environmental problems worse, as Sterman (2002) suggests.

It is worth to note that the above discussion focused on uncertainties resulting from the nature of the method and the way they are used, rather than uncertainties resulting from the technical correctness of the method. Such a discussion focus was chosen because the uncertainties resulting from the method are addressed less often by the modellers. Furthermore, they may often cause larger uncertainties than the technical ones do, as Sterman (2002) remarks. The neglect of these broader uncertainties may strengthen narrow disciplinary views and reduce the usefulness of the hydrological research. Therefore, the use of models should involve a broader methodological understanding so that the method itself does not become a substitute for disciplined thought and scientific rigour, as Funtowicz and Ravetz (1993) also state. The uncertainties related to models are further discussed by Rotmans and van Asselt (2001), Brugnach et al. (2007) and Refsgaard et al. (2007).

4.2. Disciplinary considerations

The dissertation is founded on a specific disciplinary approach, namely hydrology and water resources research. At the same time, it is recognised here that disciplinary approaches have their challenges and these are discussed in this section using research experiences from the Mekong, together with reflection from the relevant literature. In addition, cognition, values and paradigms were found to have an important role in research, and these are also briefly discussed.

4.2.1. Disciplinarity

During this research, the disciplinary approaches used were found to affect the whole research process, from the definition of the original problem to the conclusions drawn from research findings. Three specific challenges were recognised:

i) Incomplete and potentially unsustainable solutions resulting from narrow or unbalanced disciplinary approaches
ii) Poor cross-disciplinary understanding
iii) Inadequate knowledge synthesis across disciplines

The first disciplinary-related challenge, *inadequate solutions resulting from narrow disciplinary approaches*, was well recognised in Paper IV of this dissertation. That Paper investigated broad development through a model-based approach. Such approaches are usually considered to be poorly connected to social and ecological domains (Johnston and Kummu 2012). Thus, Paper IV produced an outcome that shed light mainly on hydrological and technical aspects, as the Paper also recognised. The development, such as in Paper IV, would however affect aquatic and terrestrial ecological habitats, local livelihoods and thus require broader economic and social considerations. These could not, however, be considered within the assessment approach used in Paper IV.

It is therefore obvious that the assessment presented in Paper IV is inadequate for understanding the broader impacts; and if decisions are based on such assessments alone, the consequences may be harmful. The broader implication of this example is that narrow or unbalanced disciplinary approaches provide disciplinary-dependent views and solutions, which are often inadequate. Therefore, for example, if the health of a river and its productivity are of high interest in the decision-making, model-based approaches alone most probably are not the best ones but should be complemented – and even partly replaced – by more comprehensive assessments. The model-based assessments have tended to play a large role in the Mekong, and this has been often criticised (e.g. Käkönen and Hirsch 2009).

The second disciplinary challenge, *poor cross-disciplinary understanding*, was recognised especially between the hydrological modellers and social scientists. The stereotypical view is that modellers tend to see the problems solely from the natural science perspective and they consider them to be solvable through mathematical methods and water resources management interventions. On the other hand, the social scientists are seen to perceive the problems more from a humanistic perspective, being solvable through policy and institutional arrangements. But a more important difference between the modellers' and social scientists' views may often be how the problem itself and the solutions are perceived. Modellers tend to think that the problem is commonly agreed and that it has an objective solution, whereas social scientists consider the definition of the problem and the solutions to be ambiguous, socially constructed and politically motivated (Nancarrow 2005).

Understanding challenges across disciplines was also observed between modellers and ecologists. The reason for the poor cross-disciplinary understanding was observed to originate at least from the modellers often simplified view on the river environment, whereas the ecologists are more aware of the complexity and inter-connectedness of the processes in the river environment. This mismatch in views resulted in awkward situations, where both the modeller and the ecologist have the same objective, but they couldn't find a common ground for their work, although their work is closely related. Altogether the mismatches in disciplinary views were found to form barriers, often preventing co-operation between the disciplines and thus development of more holistic solutions.

The third disciplinary challenge, *inadequate knowledge synthesis across disciplines*, was experienced in many ways in the Mekong. For example, the research findings produced by different researchers were recognised to stay within individual publications or reports, with a poor level of synthesis between the findings. One single important synthesis challenge was observed in scientifically connecting hydrological information, especially river flow information, with information from aquatic ecosystems, and thus to understand their relationship. This challenge is well recognised, and it has been difficult to solve elsewhere, too (Arthington et al. 2006; Poff et al. 2003), although the general experience shows that river flow and ecosystems are inseparably related (Bunn and Arthington 2002; Nilsson et al. 2005; Rosenberg 2000). Such a situation clearly calls for new approaches and a re-thinking of the co-operation across disciplines, as Poff et al. (2003) argued. The co-operation across disciplines in the Mekong context has been discussed further by Keskinen (2010).

4.2.2. Cognition, values and paradigms

In addition to the above-discussed challenges of disciplinary approaches, the more psychological aspects (such as cognition, values and paradigms) were found to influence the whole research process from the problem definition to the conclusions. For example, cognition was found to affect our understanding of the original problems and thus the formulation of the research questions; values were found to affect what we consider important and what we choose to include or exclude from the research; and paradigms were found to result in views where certain approaches of certain scientific disciplines are considered the most appropriate tools for solving the problems in question.

The dissertation research taught that problem-solving in the Mekong through hydrological research requires much broader thinking than merely discipline-specific thinking because the problems are highly complex, with multiple links and feedbacks within the human-technology-environment system. Thus, cognition, values and paradigms are also important discussion topics in hydrological research and not only a discussion topic for the philosophy of science. The neglect of cognition, values and paradigms would not result in their disappearance, but it would only continue to make their effects unconscious. A short introduction to cognition, values and paradigms is given in the following.

Cognition here refers to a process where sensory inputs are received, transformed, interpreted and used in each individual mind. Cognition is further elaborated by Popper (1978), who also formulated a concept of three worlds that illustrate the function of cognition. The first world is the physical world. The second world is the inner human world with its perception, mental states and ideas. The third world is a human-created world which includes the knowledge that we produce about the first world. Popper's (1978) concept of three worlds basically suggests that there is a physical world that we interpret through our senses and thinking; and on the basis of thinking, we formulate concepts to describe reality. In research, the practical significance of the interpretation of reality is on the level of agreement between our concepts and reality itself, as it determines how intelligently we are able to understand the world and co-operate with it. Hanson (1958) also noted that an observation is dependent on the conceptual framework and that preconceptions can affect observation and description. Max-Neef (2005) further proposed that reality should be considered as ambiguous and such views should be part of strong trans-disciplinarity.

Values, as defined by Cowan and Todorovic (2000), determine human ethics and action, and they can be individualistic or shared by a community. Values can range from sheer instinctive survival values to recognition of viability for all beings in a complex and sustainable world (Beck and Cowan 1996; Cowan and Todorovic 2000). The problem of human values arises when they are inconsistent with the environment (Beck and Cowan 1996). The recognition of values is also important in research as values may affect the scope, intentions and thus the outcome of the research.

Paradigms, as defined by (Kuhn 1970), are something what a community made up of individuals share and which are reinforced through the education of individuals joining the community. Paradigms may be observed, for example, among hydrologists as a tendency to automatically approach water-related problems with standard disciplinary approaches, such as modelling. Broader water-related paradigms can be observed in the development of concepts such as *Integrated Water Resources Management; Water, Food and Energy Nexus*; and *Water, Land and Energy Nexus*; and in the overall tendency to view water as having a central role. Paradigms as such can be useful principles for organising reality, but problems arise when paradigmatic views do not meet demand. In such situations, old paradigmatic views become inadequate in solving the problems in new circumstances or they address the problems only partially. For example, Pahl-Wostl et al. (2011) describe the development of paradigms in water management from a 'prediction and control paradigm' towards an 'Integrated and adaptive paradigm' to address the increasingly recognised complexity. In general, the growing environmental problems have resulted in paradigm shifts towards the need to recognise complexity and broader involvement of society in the scientific process (Gibbons 1999; Hessels and van Lente 2008; Pahl-Wostl 2007). Pahl-Wostl et al. (2011) also emphasise the importance of contributions from psychology in the understanding of the paradigms.

4.3. Future directions

Four main directions are suggested here for future hydrological and water resources research. These suggestions concern the hydrological knowledge in the Mekong, the use of mathematical models, assessment scales, a disciplinary research approach, and the importance of managing uncertainty.

4.3.1. Mathematical models

Models have played a large role in the assessment of water resources development in the Mekong (Johnston and Kummu 2012), but they have also been criticised for various reasons. For example, models have been found to be poorly connected to broader ecological and social domains (Johnston and Kummu 2012; Sarkkula et al. 2007), they produce non-transparent knowledge (Käkönen and Hirsch 2009), and they are difficult to link to practical water management (Borowski and Hare 2007) and planning and decision-making (Brugnach et al. 2007). It is argued here that the above critique has been at least partly a result of a misunderstanding of the models and knowledge they produce, the improper use of models and their results, and poor practices from the modellers' side.

Therefore, based on experience from the dissertation research and the above-presented critique in literature, the use and role of models should be re-visited. This is particularly important when the end-users of the models and their results are outside of the modelling community. Particular emphasis should be given to (i) participatory modelling approaches, (ii) the role of the models in the knowledge production process, and (iii) improved reporting of model use and their results.

Participatory modelling, involving various stakeholders, could help to inform non-modellers of the nature of the models and thus define more efficiently the key questions that modelling efforts should focus on. In addition, participatory approaches would increase the understanding of the modelling results by the non-modellers and thus increase the potential of modelling results to influence practical water management, planning and decision-making. The participatory approach would also increase the transparency and legitimacy of the use of modelling results in the eyes of the broader audience.

Re-visiting the role of the models in the knowledge production process would help to avoid the use of models as a basis for decision-making in situations where the models alone are inadequate tools for the job. For example, in the Mekong, the models have been commonly used to support decision-making and have played a central role in the assessments of water resources development (Johnston and Kummu 2012), although it is well known that they have so far been poor tools for understanding the impacts of development on ecological and social domains. Therefore, re-visiting the role of the models in the knowledge production process should aim at understanding what kind of knowledge is needed for solving a particular problem or in decision-making, and what kind of knowledge the models can produce. This would most likely benefit the development of more holistic assessment frameworks with greater emphasis on scientific rigour. The models would best serve as part of such holistic assessment frameworks by answering specific questions according to their own capabilities.

Improved reporting of model use and their results would improve the understanding and evaluation of the modelling process and its results by a broader audience and other modellers. It was recognised that conceptual maps describing the modelling process would help to understand the nature and the boundaries of the models. Reporting of simplifications and assumptions and other limitations of the models would also help to evaluate the model results and understand the related uncertainties. These aspects are considered important for all users of the model results, regardless of whether they have a science, management, planning, or policy background.

4.3.2. Assessment scales

The dissertation recognised that the spatial and temporal scales of the research may affect the conclusions and the broader applicability of the results. In the case of the spatial scales, the cumulative impacts play an important role. For example, Paper IV investigated multipurpose reservoirs in a single sub-basin, but did not consider the impacts on possible multi-purpose reservoir development on a Mekong Basin scale. The Mekong basin scale multipurpose reservoir development may lead to broader cumulative impacts, which the sub-basin scale study could not foresee. Therefore, extrapolation from the conclusions of a small scale study to larger scales may result in the neglect of cumulative impacts.

The temporal scales were found to affect the accuracy and applicability of the results.

For example, long temporal scales in hydropower assessments in Paper III and IV resulted in neglect of short-term river (daily and hourly) flow impacts, and the results suggested stable dry season flows. However, Paper IV and the study by Wyatt and Baird (2007) show that the hydropower operations have increased the hourly and daily dry season flow variability. In addition, the short temporal assessment scales of Papers III and IV may have neglected the influence of the climate variability discovered in Papers I and II. Papers I and II did not consider the influence of drier and wetter periods, and they were performed during a period with average hydrological conditions. The assessment period of Paper I, however, included hydrologically differing years, and some indications of the influence of hydrological conditions on the flow impacts of hydropower operations were discovered.

The scales can thus be another source for uncertainties, and therefore the recognition of assessment scales and their influence on research findings is important. The scale issues in hydrological assessments have been further discussed by Kummu (2008).

4.3.3. Interaction across disciplines and beyond

It was recognised that although the discipline of hydrology provides a fundamental basis for understanding the impacts of hydrological change on ecological and social systems, its usefulness depends very much on how well it is able to interact with other disciplines and a broader audience in general.

Three specific challenges were identified in Section 4.2.1: (i) *inadequate solutions resulting from narrow disciplinary approaches*, (ii) *poor cross-disciplinary understanding*, and (iii) *inadequate knowledge synthesis across disciplines*. Therefore, it is suggested that in order to make the hydrological knowledge increasingly useful, more emphasis should be put on working and interacting across disciplines as well as with the broader society. Two potential future directions are suggested: (i) the exploration of disciplinary settings, and (ii) a broader involvement of various stakeholders in the scientific knowledge production process. These directions are discussed using the work of Max-Neef (2005) and Funtowicz and Ravetz (1993).

The disciplinarity and related challenges are well discussed by Max-Neef (2005). His views also form the foundation for the term 'disciplinarity' as it is used in this dissertation. (See a description of the term 'disciplinarity' in Section 1.2.) Max-Neef (2005) recognises four standard approaches: disciplinary, multidisciplinary, pluridisciplinary and interdisciplinary (Figure 11A). The pluridisciplinary approach is also known as cross-disciplinary in the literature. These approaches differ in how much and in which way the disciplines interact with each other and how the knowledge from each discipline is synthesised. In the multidisciplinary approach, knowledge synthesis is very low because the different disciplines do not interact and there is no higher level of knowledge synthesis. In the pluridisciplinary approach, the different disciplines do interact, but they still lack a higher-level coordination. In the interdisciplinary approach, the synthesis of knowledge from different disciplines is improved by a higher-level coordination.

Max-Neef (2005) further argues that there is a need for transdisciplinary approaches to solve the complex problems that we are currently facing. He formulates an approach of 'strong transdisciplinarity', which transcends disciplinary views and recognises coordination from multiple hierarchical levels. These levels include the *empirical level*, the *purpose* or *pragmatic level*, the *normative level* and the *value level*. Max-Neef (2005) recognises an epistemological dimension as part of strong transdisciplinarity. The hierarchical levels presented by Max-Neef (2005) are shown in Figure 11B. This dissertation also adds an *epistemological level* to the hierarchy as it precedes the *value level*, as recognised also by Popper (1978) and Max-Neef (2005). The epistemological level recognises complexity, non-linear logic, and questions our conceptions of reality. In addition, as Max-Neef (2005) also recognised, the knowledge synthesis has to occur inside each individual. This also means recognising the different conceptual frameworks of different disciplines for perceiving problems and the ways they are solved, as discussed in Section 4.2.1.

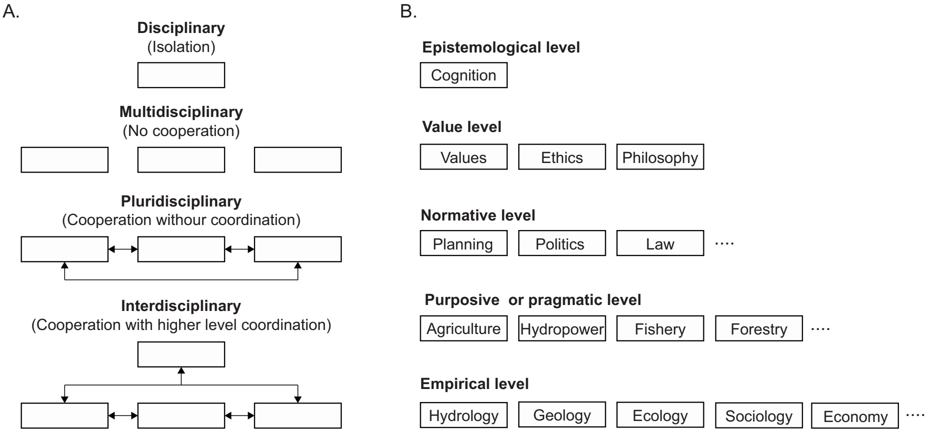


Figure 11. Disciplinarity in research: (A) Four standard disciplinary approaches, and (B) hierarchical levels for coordination in transdisciplinary research. Figure adapted from Max-Neef (2005).

The recognition of complex problems has resulted in the need to involve society more broadly in scientific knowledge production and problem-solving (Gibbons 1999; Hessels and van Lente 2008; Pahl-Wostl 2007). Funtowicz and Ravetz (1993) argued that normal science is often an inadequate problem-solving strategy and should therefore be supplemented with an appropriate ‘extended peer community’. The argument of Funtowicz and Ravetz (1993) is based on the realisation that many of our problems involve high uncertainties, high stakes and urgent decisions, but normal science is poor in addressing such situations. Funtowicz and Ravetz (1993) introduce the idea of an extended peer community that acknowledges that scientific knowledge is only one source of knowledge and other forms of knowledge should have a legitimate role in knowledge production. In the Mekong, the knowledge gap in the river flow-ecology relationship is one problem that would benefit from the expansion of the scientific knowledge base through approaches involving the extended peer community (See Section 4.3.5.).

Therefore, supplementing the scientific knowledge production process with participatory approaches involving various stakeholders (Hage et al. 2010; Reed 2008), grey literature (Uhlemann et al. 2013), expertise (Fazey et al. 2006), and local knowledge (Poulsen 2000) could be explored further. However, in the use of supplementary knowledge sources, the quality of knowledge becomes an important issue, and development of guidelines for the use and quality management of such knowledge would be necessary. Major risks for quality would be the use of non-scientific knowledge as a premise for further scientific analysis. In the worst case, such an approach may create scientific truths out of non-scientific material.

4.3.4. Uncertainty management

In the dissertation, various sources of uncertainties were recognised as being involved in the scientific process. These included errors in the data and the model, the nature of the method, the biased view of the researcher, and errors from unknowns such as the future behaviour of the climate. These uncertainties were found to affect the conclusions drawn from the scientific results and the usefulness of the research in general. The dissertation did not attempt to quantify these uncertainties, although their importance was well recognised. Therefore, it is suggested here for future direction that different forms of uncertainty should be increasingly analysed in hydrological research and managed accordingly. Uncertainty management has been well discussed by Funtowicz and Ravetz (1993), and therefore the suggestion for uncertainty management could be built upon their work.

Funtowicz and Ravetz (1993) suggested an uncertainty management framework where uncertainties were divided into technical, methodological and epistemological levels. They further argue that each of these uncertainties should be managed on different levels. Funtowicz and Ravetz (1993) formulate that technical level uncertainties correspond to 'inexactness' and can be managed on the technical level with standard routines of particular disciplines; uncertainties on the methodological level correspond to 'unreliability' and 'values' require higher-level skills related to personal judgement and professional consultancy; and uncertainties on the epistemological level border on ignorance and may be irremediable, but they should be approached through an extended peer community that also includes people other than qualified researchers. One distinct feature in these uncertainty levels is that uncertainty management towards higher levels involves the use of 'soft values' instead of the traditionally dominating 'hard facts', meaning that the problem-solving process and the resulting solutions are not based on mere facts but also has a strong emphasis on ethics and values.

The idea of Funtowicz and Ravetz (1993) of dividing uncertainties into technical, methodological and epistemological levels can potentially provide a basis for developing uncertainty management frameworks for identifying uncertainties and understanding how they should be managed. Such frameworks would give uncertainties a more central role in the research, and it could also benefit the holism of the research by addressing the facts together with the unknowns with equal weight, instead of focusing merely on the facts. The uncertainty levels are illustrated in Figure 12.

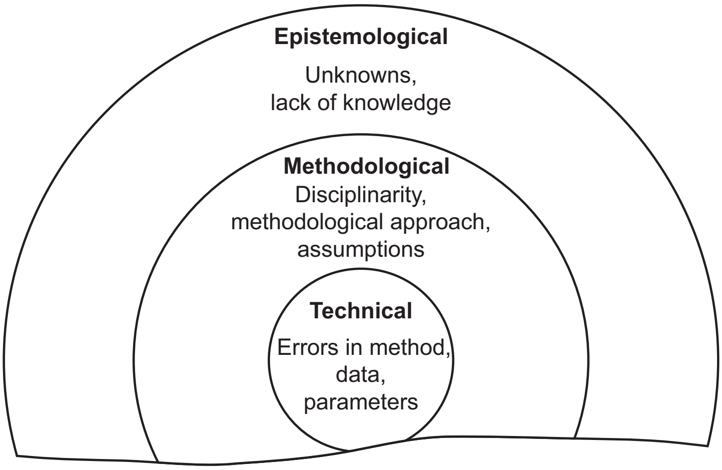


Figure 12. The three uncertainty levels with examples of individual uncertainty sources in scientific knowledge production. The idea for three levels of uncertainties is adapted from Funtowicz and Ravetz (1993).

4.3.5. Hydrological research in the Mekong

Three directions for future hydrological research were recognised. *The first research direction* is the synthesis of current hydrological knowledge. In recent years, a relatively large number of research Papers and reports have been published on the hydrology of the Mekong, but their knowledge has remained scattered and no proper synthesis has been done. The synthesis would improve the overall understanding of the Mekong's hydrology and identify knowledge gaps.

The second future direction would be to assess ongoing hydrological changes in a cumulative manner, and it would be a natural continuation from the first suggested research direction. The dissertation scratched this topic only on the surface, but it recognised that the climate and the direct human actions of hydropower and irrigation development can result in cumulative impacts where the two factors together can cause larger impacts than either one of those alone. Various cumulative hydrological impact assessments have been conducted in the Mekong (Hoanh et al. 2010; Lauri et al. 2012; Piman et al. 2013), but most of those have focused only on two or three change factors at a time with a relatively coarse scale. Especially the impact of climate variability on hydrology has been commonly neglected in these assessments. Therefore, it is suggested here that future research on cumulative impacts could start by recognising the most critical hydrological parameters that support or endanger ecological and social functions. Then it could proceed to assess the cumulative impacts on these parameters. In addition, the cumulative impact assessment should include uncertainty assessment that identifies different sources and types of uncertainties as recognised in Section 3.3 and in Section 4.3.4. Emphasis should be given especially on differentiating between uncertainties originating from the natural variability of assessed system and uncertainties which are more on the epistemic level (Merz and Thieken 2005).

*The third future directio*n is bridging knowledge gaps between hydrology, ecology, local livelihoods and the economy. The importance of hydrology to ecology, local livelihoods and the economy are well recognised in the Mekong (MRC 2010), but research evidence on this matter has remained somewhat scarce. For example, major efforts have been put into modelling to predict future flows in the Mekong, but little research evidence has been produced on the impacts of these flow changes on aquatic ecology, although their general principles are well known (Bunn and Arthington 2002; Junk et al. 1989; Lamberts 2008; Nilsson and Berggren 2000; Rosenberg 2000; Welcomme and Halls 2004). However, a few promising exceptions exist (Arias et al. 2014a; Holtgrieve et al. 2013). It has been recognised that the simple environmental flow rules have often been inadequate to address the complexity of ecosystems (Arthington et al. 2006). Therefore, it is suggested here that new approaches, which transcend single discipline views, should be sought. Such approaches are discussed by Poff et al. (2003), who emphasise the role of controlled experiments in existing and planned projects, co-operation among scientists, synthesis of results across studies for broader generalisations, and broader involvement of other stakeholders. In the Mekong, the ongoing hydropower development provides a good opportunity for controlled experiments, but this would require improved co-operation from the governments and project developers and owners.

5. CONCLUSIONS

On a general level, this dissertation had two main research frameworks. The first framework was based on hydrology water resources research and aimed at filling hydrological research gaps in the Mekong. The second framework had a philosophical approach and discussed disciplinarity and the discipline specific standard methods (statistics and mathematical models) and their effects on hydrological knowledge production. The findings of this dissertation strongly suggest that in the most recent decades the Mekong has experienced exceptional levels of climate-related hydrological variability and that the Mekong is entering a new hydrological era, where humans have become a major source of hydrological changes. In these hydrological changes the hydropower development plays an important role. The ongoing and future hydrological changes are likely to impact negatively the ecology and productivity ecosystems and thus affect the societies and food security in the region. The summary of the new findings and final remarks are presented in the following.

5.1. New findings

The dissertation contributed to past research on ENSO (Darby et al. 2013; Kiem et al. 2004; Xue et al. 2011) and climate-related hydrological variability (Buckley et al. 2007; Buckley et al. 2010; Cook et al. 2010; Fan et al. 2008; Fang et al. 2010; Sano et al. 2009) in the Mekong by examining the detailed connection of ENSO to the spatial and temporal characteristics of the rainfall and flood pulse; by performing a long-term hydrological analysis in the Mekong on basin-scale; by analysing the most recent hydrological variability in the light of the past long-term variability; and by linking the most recent hydrological variability to ENSO.

It was found that ENSO is one significant factor affecting the spatial distribution of the rainfall and the flood pulse characteristics of the Mekong. The rainfall was found to decrease during El Niño and increase during La Niña events especially in the southern parts of the Basin and during the second (i.e. the decay) year of the events. The effect of ENSO was significant also in the flood pulse characteristics. El Niño decreased the annual flow volume, peak flood and the flood duration by delaying the start of the flood season. The effects of La Niña on flood pulse characteristics were opposite to El Niño. The flood pulse characteristics can also be considered to indicate the characteristics of the timing and intensity of the monsoon rainfall.

The research on the long-term climate-related variability revealed that the hydrology of Mekong Basin has varied between multi-annual and decadal lengths of wetter and drier periods over the past seven hundred years. Recently, the Mekong has been going from a drier period towards a wetter period. But more importantly, the long-term analyses revealed that the inter-annual hydrological variability in the Mekong has increased significantly during the most recent decades, which was attributed at least partially to increased ENSO activity. The analyses suggest that the recent levels of variability may not have been experienced before in the Mekong, at least in the past seven hundred years. The increased ENSO activity has been attributed in the literature to be a result of the global warming (Cai et al. 2014; Li et al. 2013).

In the case of the assessment of the river flow impacts of hydropower development, the dissertation contributed to past research (Arias et al. 2014b; Hoanh et al. 2010; Lauri et al. 2012; Piman et al. 2012; Piman et al. 2013; Ty et al. 2011) i. by developing an advanced assessment approach that considers optimisation of power production and cascade and multipurpose operations, ii. by assessing the downstream river flow impacts of the largest hydropower cascade in the Mekong, the Lancang-Jiang cascade in China and iii. by assessing the downstream river flow impacts of a cascade of multipurpose reservoirs using Sesan tributary of the Mekong in Vietnam and Cambodia as a case study. The past research did not focus specifically on the Lancang-Jiang cascade and its impacts far downstream of the Mekong (e.g. in Cambodia) and they did not consider power production, cascade and multi-purpose operations in their assessment methods. Thus the assessments of the river flow impacts of hydropower development in this dissertation can be considered to be based on more comprehensive assessment methods than the assessments in the past research.

The assessment of the Lancang-Jiang hydropower cascade revealed that the cascade may increase the dry season flows by 34-155% and decrease the wet season flows by 29-36% at Chiang Saen at the border between China and Thailand. These estimates of the impacts are slightly higher than the estimates in the past research (Hoanh et al. 2010; Lauri et al. 2012). The assessment of the Lancang-Jiang cascade revealed also that the river flow impacts were observable in the dry season flows as far downstream as the floodplains of Cambodia, where the flows increased as much as 40-50% in March-April.

In the case of the multipurpose reservoirs, it was found that the multipurpose reservoirs can facilitate irrigation with minor losses in power production (0.6-3.4%), but they introduce new problems: the river flow impacts of irrigation become easily masked by the larger impacts of hydropower operations; the irrigation from hydropower reservoirs results easily in irrigation rates that cannot be sustained by the natural river flow regimes (i.e. without hydropower dams in place); competition between water users increase; and that the multipurpose reservoirs increase the complexity that result in greater need to consider the connections to ecological and social domains. These findings on the river flow impacts of the hydropower development are characteristic for a monsoon driven river and may therefore benefit other river basins in monsoon Asia.

In addition, this dissertation provided new insights into the cumulative impacts of climate-related hydrological variability and hydropower development. It was found that ENSO-related climate variability together with hydropower operations may jointly contribute to the increase in inter-annual dry season flow variability, the delay of the flood season, and the decrease in the amplitude of the annual flood pulse. These cumulative impacts can be however elusive due to uncertainties in hydropower operations and ENSO occurrences, but they can nevertheless result in unexpected and harmful consequences.

5.2. Final remarks

The ongoing and future hydrological changes and their complex impacts on ecology and society in the Mekong highlight the importance of understanding the implications of disciplinary research. In the case of hydrological and water resources research and hydrological knowledge production in general, this means recognising that the research based on single discipline provides often only partial solutions that do not embrace adequately the full complexity of human-technology-environment systems. In the worst case partial solutions may not contribute to the overall sustainability. Therefore, hydrological and water resources research requires broader transdisciplinary thinking that recognises the limitations in scientific methods and in our understanding of the human-technology-environment systems, especially when addressing such complex problems as in the Mekong. This further implies that the education on hydrology and water resources needs to be constantly developed so that it corresponds to the evolving challenges that we are facing.

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