IWMI
RESEARCH
REPORT

136

Climate Change, Water and Agriculture in the Greater Mekong Subregion

Robyn Johnston, Guillaume Lacombe, Chu Thai Hoanh, Andrew Noble, Paul Pavelic, Vladimir Smakhtin, Diana Suhardiman, Kam Suan Pheng and Choo Poh Sze

IWMI Celebrating 25 years 1985-2010

International Water Management Institute

WorldFish CENTER

Research Reports

The publications in this series cover a wide range of subjects—from computer modeling to experience with water user associations—and vary in content from directly applicable research to more basic studies, on which applied work ultimately depends. Some research reports are narrowly focused, analytical and detailed empirical studies; others are wide-ranging and synthetic overviews of generic problems.

Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI staff, and by external reviewers. The reports are published and distributed both in hard copy and electronically (www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

About IWMI

IWMI's mission is to improve the management of land and water resources for food, livelihoods and the environment. In serving this mission, IWMI concentrates on the integration of policies, technologies and management systems to achieve workable solutions to real problems—practical, relevant results in the field of irrigation and water and land resources.

IWMI Research Report 136

Climate Change, Water and Agriculture in the Greater Mekong Subregion

Robyn Johnston, Guillaume Lacombe, Chu Thai Hoanh, Andrew Noble, Paul Pavelic, Vladimir Smakhtin, Diana Suhardiman, Kam Suan Pheng and Choo Poh Sze

International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

The authors: Robyn Johnston is a Senior Researcher in water resources and Vladimir Smakhtin is a Principal Scientist in hydrology and water resources both at the International Water Management Institute, Colombo, Sri Lanka. Andrew Noble is Regional Director, IWMI Southeast and Central Asia; Chu Thai Hoanh is a Principal Researcher in water resources; Guillaume Lacombe is a Postdoctoral Fellow in hydrology; and Diana Suhardiman is a Postdoctoral Fellow in political ecology both at IWMI Southeast Asia in Vientiane, Lao PDR. Paul Pavelic is a Senior Researcher in hydrogeology at IWMI South Asia in Hyderabad, India. Kam Suan Pheng is a Senior Scientist in geographical information systems (GIS) and Choo Poh Sze works as a consultant, both at the WorldFish Center in Penang, Malaysia.

Johnston, R.; Lacombe, G.; Hoanh, C. T.; Noble, A.; Pavelic, P.; Smakhtin, V.; Suhardiman, D.; Pheng, K. S.; Sze, C. P. 2010. *Climate change, water and agriculture in the Greater Mekong Subregion*. Colombo, Sri Lanka: International Water Management Institute. 60p. (IWMI Research Report 136). doi:10.5337/2010.212

/ climate change / water resource management / adaptation / indicators / river basins / water availability / water quality / groundwater / fisheries / ecosystems / water power / population growth / irrigation growth / South East Asia / Greater Mekong Subregion /

ISSN 1026-0862
ISBN 978-92-9090-728-2

Cover photograph shows rice cultivation in Kampong Thom, Cambodia *(Photo credit:* Chu Thai Hoanh).

Please send inquiries and comments to: iwmi@cgiar.org

Acknowledgements

This report is partially drawn from a broader study commissioned by the Swedish International Development Cooperation Agency (Sida) on the interactions between agriculture, environment and climate change in the Greater Mekong Subregion (GMS), reported in Johnston et al. 2009. We gratefully acknowledge funding provided by Sida. We are also grateful to Sumith Fernando, Sarath Gunasinghe (IWMI, Colombo) and Sreedhar Acharya (IWMI, Hyderabad) for redrawing maps and diagrams; and to Kingsley Kurukulasuriya for editing the final draft of the document.

Partners

The following organizations collaborated in the research conducted for this report.

International Water Management Institute

WorldFish Center, Penang, Malaysia

Donors

This report was based on the research funded by:

(a) Swedish International Development Cooperation Agency (Sida)

(b) The core funds of IWMI during 2009, which consisted of contributions from the following countries and organizations:

- Australia
- Canada
- DFID
- France
- Germany
- India
- Ireland
- Japan
- Netherlands
- Norway
- South Africa
- Sweden
- Switzerland
- USAID
- World Bank

Contents

Acronyms

ADB	Asian Development Bank
ASEAN	Association of Southeast Asian Nations
AWM	Agricultural water management
CA	Comprehensive Assessment of Water Management in Agriculture
CGIAR	Consultative Group on International Agricultural Research
CURE	Consortium for Unfavorable Rice Environments
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO on-line statistical database
GCM	General Circulation Model
GCP	Global Carbon Project
GDP	Gross domestic product
GHG	Greenhouse Gas
GMS	Greater Mekong Subregion
IPCC	Intergovernmental Panel on Climate Change
IRRI	International Rice Research Institute
IUCN	International Union for the Conservation of Nature
IWMI	International Water Management Institute
MAF	Lao PDR Ministry of Agriculture and Forestry
MAFF	Cambodian Ministry of Agriculture, Forestry and Fisheries
MARD	Vietnamese Ministry of Agriculture and Rural Development
MIME	Cambodian Ministry of Infrastructure, Mines and Energy
MoE	Cambodian Ministry for Environment
MONRE	Vietnamese Ministry of Natural Resources and Environment
MOWRAM	Cambodian Ministry of Water Resources and Management
MRC	Mekong River Commission
msl	mean sea level
NAPA	National Adaptation Program of Action to Climate Change
REDD	Reducing Emissions from Deforestation and Forest Degradation
SEI	Stockholm Environment Institute
Sida	Swedish International Development Cooperation Agency
SRES	Special Report on Emissions Scenarios
START	Global Change System for Analysis, Research and Training
TEI	Thailand Environment Institute
UNDP	United Nations Development Programme
UNEP	United Nationals Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WB	World Bank
WREA	Lao PDR Water Resources and Environment Administration
WRI	World Resources Institute
WWF	World Wildlife Fund

Summary

The report reviews the current status and trends in water management in the Greater Mekong Subregion (GMS); assesses likely impacts of climate change on water resources to 2050 based on historical patterns and simulated projections; examines water management strategies in the context of climate and other changes; and identifies priority actions for governments and communities to improve resilience of the water sector and safeguard food production.

The impacts of climate change in Southeast Asia on agriculture and food production will be largely mediated through water, but climate is only one driver of change. Rapid economic development and population growth mean that water resources in the region will be shaped by a complex mixture of social, economic and environment factors. The magnitude of these changes is at least the same as, or greater than, those driven by climate change and will occur in a shorter timespan.

Current climate models indicate no clear regional trends in rainfall and water availability, and the degree of uncertainty associated with projections is very high. Given this, it is more useful to characterize likely change as an increase in the variability and uncertainty of water availability and to take a “no regrets” approach to water management, with actions to improve both water productivity and access to on-farm and off-farm storage (both surface water and groundwater) and reduce water-related risks.

National governments see expansion of irrigation as an important priority to increase agricultural production and reduce risk from climate change, but water management must go beyond irrigation. Rain-fed agriculture dominates crop production in the GMS, and improvements in water management for rain-fed systems are likely to be the most cost-effective strategies in increasing food production in the region. Because of the importance of the freshwater capture fisheries to regional food security, freshwater ecosystems must be seen as an integral part of agricultural production systems and managed accordingly. This requires attention not only to environmental flows but also to fish migration paths, and wetland habitat coherence and connectivity at the landscape scale.

Proposed hydropower development in the major river basins of the GMS will result in changes to river flows at a previously unprecedented scale and rate. In the Mekong, the projected increase in the discharge during the low-flow season is larger than projected irrigation demands from all Lower Mekong countries and could provide significant opportunities for irrigation development. However, the importance of freshwater fisheries to food security in the region underscores the importance of protecting the productive capacity of freshwater ecosystems from the impacts of hydropower and other developments.

Adaptation to climate change will take place in a highly dynamic and uncertain context. There are no defined boundaries between climate-specific and non-climate-specific adaptations. Response strategies must be formulated in the context of the whole range of impacts and drivers. A robust approach to adaptation is needed, seeking solutions that address current problems in a manner that builds resilience regardless of the direction of change. One of the major factors determining resilience is economic status and, therefore, poverty reduction is critical to underpinning adaptation efforts in all sectors.

Climate Change, Water and Agriculture in the Greater Mekong Subregion

Robyn Johnston, Guillaume Lacombe, Chu Thai Hoanh, Andrew Noble, Paul Pavelic, Vladimir Smakhtin, Diana Suhardiman, Kam Suan Pheng and Choo Poh Sze

Introduction

The Greater Mekong Subregion (GMS) comprises the five mainland Southeast Asian nations of Cambodia, Lao PDR, Myanmar, Thailand and Vietnam; plus the southern Chinese province of Yunnan, which is the source of four of the region's five major rivers (Figure 1). It is home to a population of around 275 million, and rapid development over the last 20 years has made it a new frontier of Asian economic growth (ADB-GMS 2010).

A spate of recently published reports (e.g., ADB 2009a; WWF 2009; TKK and SEA START RC 2009; Eastham et al. 2008) reflects growing international concern about the potential impacts of climate change in this region, which is highly dependent on agriculture and fisheries for food security and income generation. These sectors are particularly vulnerable to changes in climate. Impacts of climate change on agriculture and food production will be largely mediated through water, and most countries in the region have identified water resources as a priority sector under National Adaptation Plans of Action (NAPAs; see, e.g., MOE 2005; MONRE 2008; WREA 2008).

Effective strategies for adaptation in the water sector to safeguard food production are not clear-cut. Neither the direction nor the magnitude of projected changes in water availability is well established. The region's water resources are already undergoing rapid change as a result of other pressures such as population growth and economic development, and all countries have ambitious plans for water resources development in the next 10-20 years. Climate change is only one driver of change, and adaptation will occur in a highly dynamic social, economic and policy environment.

This report addresses the following questions:

- What are the projected impacts of climate change on water resources in the GMS in the short to the medium term (to 2050)?
- How do these relate to other changes impacting on the water sector?
- What are the most effective adaptation strategies in the water sector to safeguard food production in the context of climate and other changes?

The report reviews the current status and trends in water management in the region; assesses likely impacts of climate change on water resources, based on historical patterns and modeled projections; examines water management strategies in the context of climate and other changes; and identifies priority actions for governments and communities to improve the resilience of the water sector and safeguard food production. It focuses primarily on the short to the medium term, since decisions taken now will lay the foundation for longer-term adaptation. It draws upon a broader study on the interactions between agriculture, environment and climate change conducted by IWMI for the Swedish International Development Cooperation Agency (Sida), reported in Johnston et al. 2009.

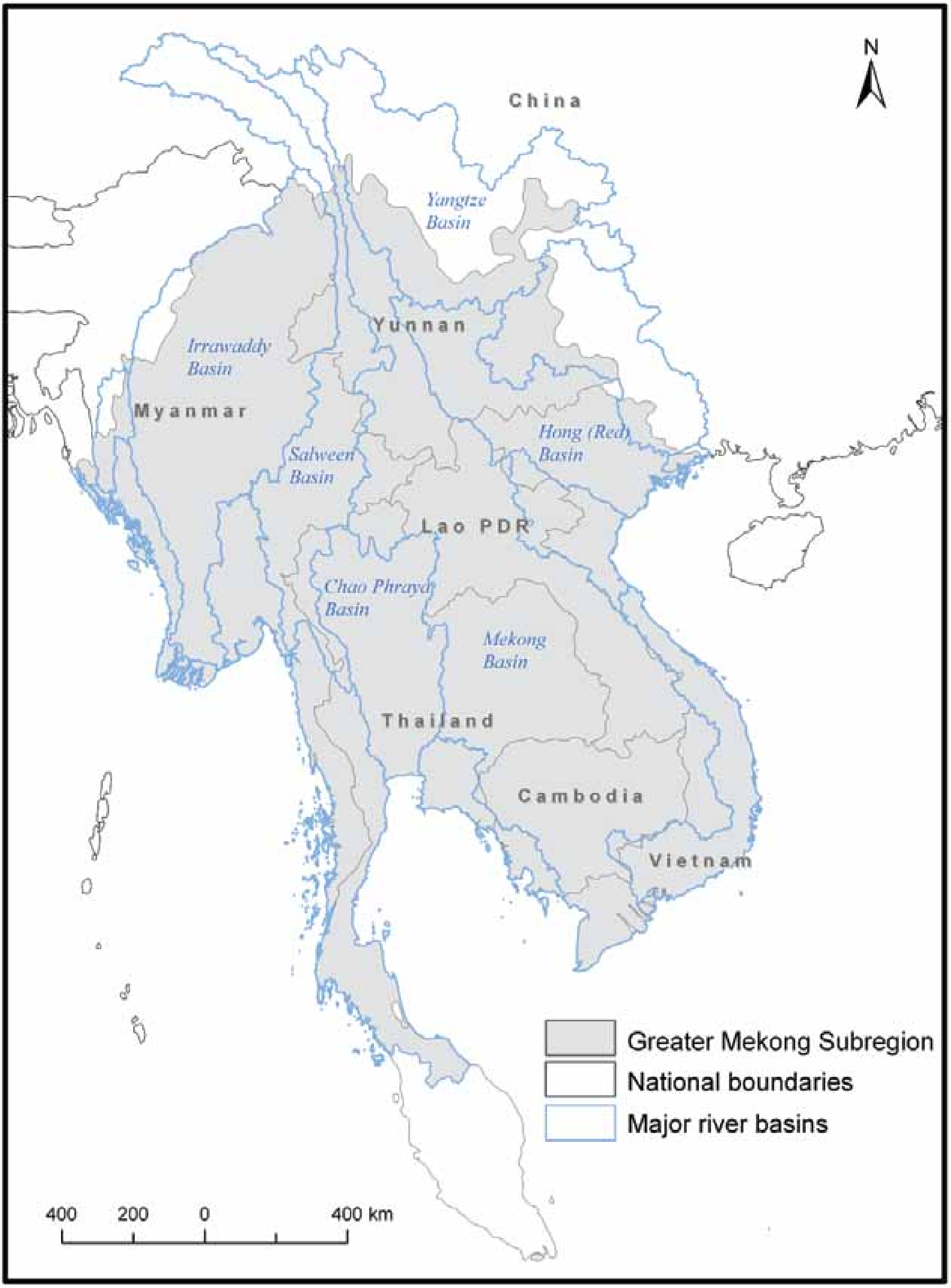


FIGURE 1. The Greater Mekong Subregion (GMS).

Water Resources in the GMS: Status and Trends

Water resources in the GMS are abundant but spatiotemporally unequally distributed. All countries in the GMS have strong monsoonal climates, with up to 90% of the year's total precipitation occurring during the wet season (May to October; MRC 2005; FAO 2008). Average annual rainfall varies from 700 mm in the dry zone of Myanmar to more than 5,000 mm at some places in the coastal regions of Cambodia, Myanmar and Vietnam (MRC 2005; FAO 2008; SCW 2006).

Table 1 sets out summary statistics for water resources in GMS countries. In terms of total water resources, all GMS countries lie well above the level at which water availability is considered to be a constraint to development (1,700 m^3 per capita; Falkenmark and Widstrand 1992). However, the Comprehensive Assessment of Water Management in Agriculture (CA 2007) ranked all countries except Thailand and Yunnan Province of China as economically water-scarce, i.e., human, institutional and financial capital limits access to water, even though sufficient water is available to meet human demands.

The GMS includes five major river basins (the Mekong, Irrawaddy, Salween, Red (Hong) and Chao Phraya) as well as a large number of smaller coastal rivers[1] (Figure 1). Physiographically, the region can be considered in terms of five broad agroecological zones which share common water resource characteristics and agricultural production systems. These are not rigidly defined, but are a useful construct for discussing systems at the regional scale. They are shown schematically in Figure 2 and major characteristics are set out in Table 2; and described in more detail in Johnston et al. 2009:

- The *mega-deltas* of the Red, Chao Phraya, Irrawaddy, Salween and Mekong rivers and the Tonle Sap floodplain.
- The *plains* and *plateaus* of the Isan Region of Northeast Thailand, Central Thai Plain, Myanmar dry region, Lao PDR, Mekong floodplains, and North and Northeast (NE) Cambodia.
- The *upland regions* above 250 m altitude, including:
    - o *intensively farmed uplands* of Yunnan, Northern Thailand, Central Highlands of Vietnam and Bolavens Plateau in Lao PDR.
    - o *forested uplands* of Northern Lao PDR, Eastern and Western Hills in Myanmar, and Northwest (NW) Vietnam and Yunnan.
- *Coastal zones* - narrow coastal plains rising rapidly to coastal ranges, usually within 50 km of the ocean (Vietnam, Cambodia, Thailand, Myanmar).

The three major water-dependent sectors in the GMS are agriculture, fisheries and hydropower. Though important in social and economic terms, industrial, domestic and municipal withdrawals are relatively minor (Table 1) and do not impinge significantly on agricultural production or food security, and are therefore not considered in this study.

---

[1] Northern and eastern parts of Yunnan lie within the Yangtze and Xun Jiang river basins.

TABLE 1. Water-related indicators for GMS countries.

	Unit	Source	Cambodia	Lao PDR	Myanmar	Thailand	Vietnam	China
Population 2007	Million	World Bank 2009a	14.45	5.86	48.78	63.83	85.14	1,319.98
Projected population 2050	Million	Earthtrends 2009	25.11	9.29	58.71	67.38	119.97	1,408.85
GDP per capita at PPP (current international $)	$	ADB 2009b	2,030	2,387	888[1]	8,216	2,788	5,958
GDP per capita growth rate 2002-2007		ADB 2009b	8.6	5.0	11.0[1]	4.8	6.5	10.1
GDP from agriculture (2008)	%	ADB 2009b	32.5	32.1	46.7	11.6	22.1	11.3
Agricultural population (2006)	%	FAO 2009b	68	76	69	45	65	64
Total land area	km^2	World Gazetteer 2009	178,035	230,800	657,740	511,770	325,360	9,326,410
Population density 2007	Persons/km^2	Calculated	81	25	74	125	262	142
Arable land 2007	km^2	FAO 2009b	38,000	11,700	105,770	152,000	63,500	1,406,300
Arable land per capita 2007	ha/person	Calculated	0.26	0.20	0.22	0.24	0.07	0.11
Area equipped for irrigation as % of arable land 2007		FAO 2009b	8	26	21	33	47	41
Population below US$2.00 (PPP) per day	%	ADB 2008	61.7	74.4	--	25.8	43.2	37.8
Year			2004	2002	--	2002	2004	2004
Internal renewable water resource	km^3/yr	FAO 2009a	121	190	881	210	366	2,812
Total actual renewable water resource	km^3/yr	FAO 2009a	476	334	1,046	410	891	2,830
Per capita water resources 2007	m^3/person	FAO 2009a	33,537	57,914	21,613	6,462	10,338	2,130
Average annual precipitation	mm/yr	FAO 2009a	1,904	1,834	2,091	1,622	1,821	--
Total annual water withdrawal	km^3/yr	FAO 2009a	4.08	3.00	33.20	87.10	71.40	630
Per capita annual water withdrawals	m^3/person/yr	FAO 2009a	308	555	711	1,412	877	486
Withdrawn for agriculture	%	FAO 2009a	98	90	98	95	68	68
Withdrawn for industry	%	FAO 2009a	1	6	1	2	24	26
Withdrawn for domestic use	%	FAO 2009a	2	4	1	2	8	7

(Continued)

TABLE 1. Water-related indicators for GMS countries (continued).

	Unit	Source	Cambodia	Lao PDR	Myanmar	Thailand	Vietnam	China
Urban population with access to improved water source 2004	%	Earthtrends 2009	64	79	80	98	99	93
Rural population with access to improved water source 2004	%	Earthtrends 2009	35	43	77	100	80	67
Total population with access to improved sanitation 2004	%	Earthtrends 2009	17	30	77	99	61	44

[1] GDP figures for Myanmar are for 2007.

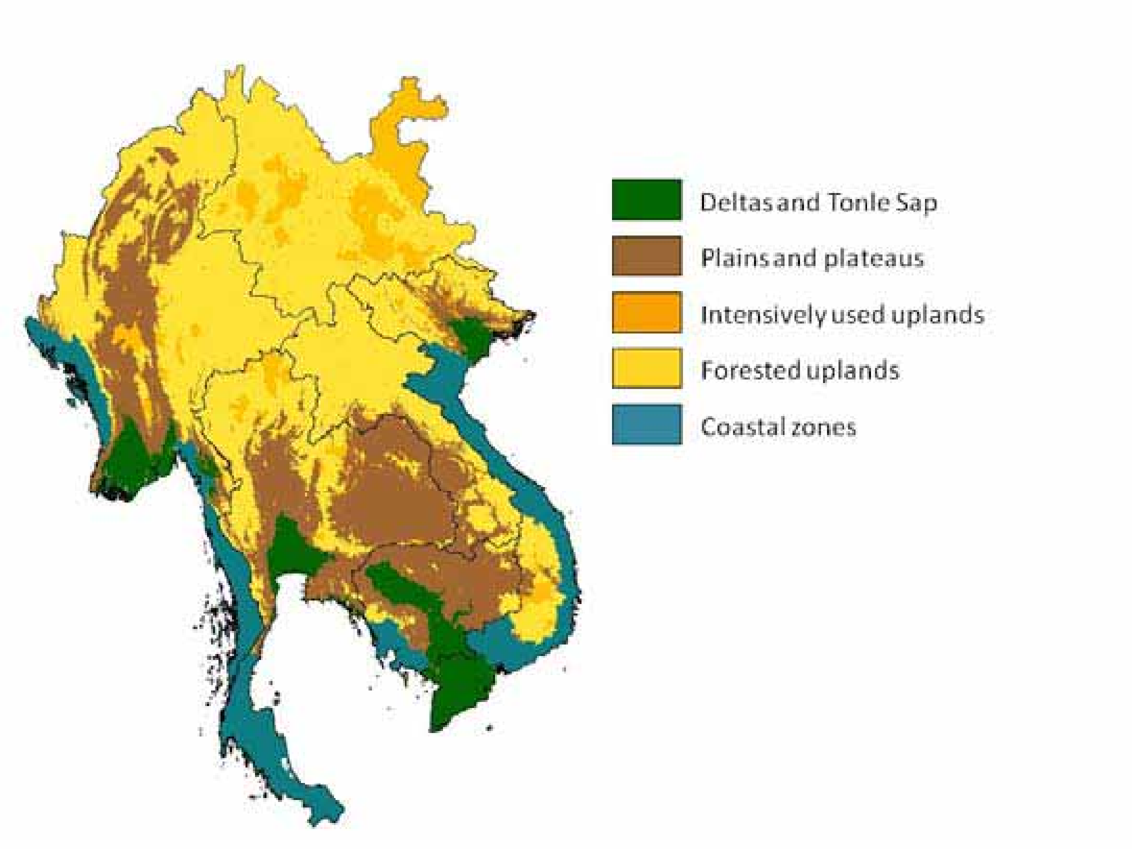


FIGURE 2. Agroecological zones of the GMS.

Water and Agriculture

Agriculture is by far the largest consumer of water in all GMS countries, estimated to account for 68% (in Vietnam and China) to 98% (in Cambodia) of total withdrawals (WRI 2009; Table 1). Despite this, the proportion of irrigated land in GMS countries is relatively low by world standards (ranging from 7% of total cropland in Cambodia to 31% in Vietnam; World Bank 2009a) and rain-fed agriculture dominates production. Agriculture in the GMS is thus particularly vulnerable to climate variability, with significant risk from both floods and droughts even under current climate conditions. Safeguarding production will require improvements in water management in both rain-fed and irrigated systems.

Agriculture in Southeast Asia is in transition from traditional subsistence systems to modern commercial production of a wide range of commodities for both local consumption and export, with significant implications for water demand and water quality. Agricultural production in the GMS over the last 20 years has seen steady increases across all subsectors and all countries. Production in major commodity groups has more than doubled since 1990, outpacing the region's rapid population growth (FAO 2009b; see Johnston et al. 2009 for a more detailed discussion of agricultural trends). Most of this remarkable increase has come from intensification and increases in yield, rather than from expansion in agricultural area, which grew by less than 5% over the same period (FAO 2009b). Increases in crop yield have resulted from the range of new technologies and approaches that underpinned the 'green' revolution (IRRI 2008): uptake of improved varieties; increasing use of fertilizers; improved farming practices; and the expansion and more efficient use of irrigation.

TABLE 2. Characteristics of major physiographic zones of the GMS.

	Deltas and Tonle Sap*	Lowland plains and plateaus	Uplands		Coastal areas
			Intensively used uplands	Forested uplands	
Main administrative/ statistical reporting area in each zone no.	Mekong Delta Tonle Sap floodplain Chao Phraya Delta Red River Delta Irrawaddy, Salween deltas	North + Northeast Cambodia Vientiane and Savannakhet plains Central MM North (part) of Thailand + NE Thailand Southeast Vietnam	Yunnan Bolavens Plateau, Lao PDR Northern Thailand Myanmar Hills + Shan Plateau Northeast, Northwest Central Highlands of Lao PDR Vietnam	Yunnan North Lao PDR and Annamite range in NW Vietnam Southern and Central North Central, South Myanmar Hills NW Vietnam	Cambodian Coast (Kampot, Kep, Koh Kong) Coast (Rakhine, Mon, Thanintharyi) Southern Thailand Central + SE Vietnam
Area	< 10% of GMS land	~25% of GMS land	~15% of GMS land	~40% of GMS land	~10% of GMS land
Elevation	< 20 m	< 250 m	> 250 and < 2.000 meters (m)	> 250 m	0-1,000 m
Population	86 million (31% of GMS)	64 million (23% of GMS)	89 million (32% of GMS, 46 million in Yunnan)	4 million (2% of GMS)	33 million (12% of GMS)
Population	Each hosts a major city. > 18 million urban people. Generally high population density – very high in Red River Delta	Moderate density (50–150 persons per km^2, except in Cambodia with < 10). Area with greatest numbers of poor	> 100 persons per km^2 in permanently farmed uplands	< 100 persons per km^2 Dominated by ethnic minorities. Very high poverty rates (> 30% in Yunnan and > 75% in other countries) but low total number	Moderately high density (>100) except on Myanmar Coast
Main characteristics and functions	Rice production (irrigated and rain-fed) – nearing full production, problems of intensification, flooding, high population density	Mixed agricultural systems with wet-season rice plus a second dry-season crop (irrigated rice, sugarcane, maize, legumes, pulses, cassava), stubble grazing and plantations (sugarcane, oil crops, rubber, timber and pulpwood)	Intensively farmed uplands with wide range of suitable crops in subtropical to temperate conditions at increasing altitudes. Agroforestry options	Dominantly forest with shifting cultivation and livestock grazing. Sloping lands with high rates of erosion when cleared	Narrow coastal plains rising rapidly to coastal ranges with short, steep rivers with small watersheds (<50 km^2). Mixed production systems with a high proportion of agro-industrial and tree crops

* Tonle Sap and floodplain in Cambodia are grouped with deltas because of close hydrological links to the Mekong Delta and similar production systems.

All national governments see expansion of irrigation as an important priority, to increase production and reduce risk from climate change. FAO statistics indicate that irrigated area in the region (excluding Yunnan) increased by at least 1 million hectares (Mha) between 1990 and 2003 (World Bank 2009a), but national figures suggest an even larger increase. UNDP (2006) reports that government programs in Myanmar have doubled the area under irrigation over the last 20 years to 1.4 Mha; and the Cambodian government estimates that over 0.73 Mha of land now have access to irrigation compared to less than 0.25 Mha in 1990 (MAFF and MOWRAM 2007; FAO 2009b).

The largest irrigated areas are found in the mega-deltas and low-lying floodplains of the Red, Mekong, Chao Phraya and Irrawaddy rivers, the “rice-bowls” of the region. Although they constitute only 10% of the total land area, they produced almost 50 million tonnes of rice in 2005, half of the region’s production (excluding Yunnan) and around 8% of the global crop (FAO 2009b; national government statistics). In these areas, complex systems of dykes, levees and canals are used to divert and retain the floodwater of the monsoon. Only the Red and Chao Phraya deltas have significant upstream storages to regulate supply (Water Resources e-Atlas 2003). Cultivation of traditional wet-season rice with supplementary irrigation is increasingly being replaced by fully or partially irrigated crops before and after the wet season, taking advantage of higher solar radiation and lower flood risk. For example, in the Mekong Delta, the traditional (long duration) wet-season rice crop has declined to only 10% of total production, which is now dominated by two irrigated crops in winter-spring and summer-autumn (Government Statistical Office of Vietnam 2009). This trend has produced significant increases in both yield and total production, but places water resources under stress.

The extent and success of irrigation development in the inland plains and plateaus have been more variable. In Thailand, there has been substantial investment in irrigation storage for the inland plains, with large multipurpose storages in both the Chao Phraya Basin and the Isan Plateau, and thousands of small dams and reservoirs servicing small to medium schemes (Molle 2004). Despite this, the area planted to dry-season irrigated crops is significantly lower than the total irrigable area. Similarly, in Cambodia the majority of irrigation schemes in the inland plains around Tonle Sap are used mainly for supplementary irrigation of wet-season rice; only 13% of the total rice crop is grown in the dry season, mostly on the Mekong floodplains in the south (MAFF 2009b). In Myanmar, programs begun in the 1980s have expanded irrigation to cover approximately 25% of crop area, with significant development in the inland plains of Sagaing, Magway and Mandalay provinces (UNDP 2006; FAO 2008). However, irrigation intensity is generally suboptimal, for example, the Sedawgyi Dam project runs at 61% of its total command area, with the remaining area utilized as rain-fed (UNDP 2006). Low uptake of dry-season irrigation in the region is attributed to a mixture of factors including inappropriate infrastructure, a lack of farmer knowledge of dry-season cultivation techniques, other labor opportunities in the dry season (seasonal migration to the cities) and operation and maintenance (O&M) problems.

Small- to medium-scale irrigation, mainly pumped directly from rivers, is common in the intensively farmed upland river valleys of Northern Thailand and Yunnan, for high-value horticultural produce and other cash crops. Groundwater irrigation in the Central Highlands of Vietnam and the Bolavens Plateau of Lao PDR has allowed the establishment of large areas of coffee, but overexploitation has threatened the sustainability of groundwater resources in some areas. Similar threats have recently been observed in the lower northern region of Thailand due to excessive groundwater pumping to support year-round rice production. In other areas of the uplands, irrigation is generally limited, and usually very small-scale.

Overall, withdrawals are only a small fraction of total renewable resources (maximum of 22% in Thailand; Table 1), but demand for agricultural water is increasing and the strongly seasonal patterns of rainfall and irrigation demand mean that seasonal shortages are common. Pech and

Sunada (2008) estimate that more than 80% of flows are extracted for irrigation in the Mekong Delta during the critical dry-season months of March-April, resulting in local shortages and intrusion of seawater. Both the Chao Phraya and the Red are essentially "closed" basins (Molle 2004). In the Isan Plateau in NE Thailand, seasonal water shortages have led to conflict between urban and agricultural users (MRC-TNMC 2004).

The current trend towards the establishment of large commercial plantations (for rubber, oil palm, cassava, coffee and other crops) is also likely to impact on agricultural water demand. Concessions to develop plantations have been granted over large areas of land, particularly in Cambodia and Lao PDR (Rutherford et al. 2008; MAFF 2009a; MPI 2008). It is not clear what the ultimate impact of these plantations will be on water availability and demand. Most of the current development is rain-fed, but at least some of the investment deals have included funding to build irrigation infrastructure: e.g., the Kuwaiti loan of $546 million to Cambodia to build an irrigation dam on the Stung Sen (Economist 2008); and Chinese loans to Myanmar to construct joint hydropower and irrigation infrastructure (International Rivers 2009). Even if large-scale irrigation is not developed, the impacts of widespread conversion of forest or grassland to agriculture on runoff and water use are likely to be significant, though difficult to predict. Clearing generally increases runoff, while reforestation (or establishment of tree crops) has been demonstrated to decrease overall water yield from catchments by up to 30% per year in tropical southern China (Sun et al. 2006).

Water quality in most of the region is generally not limiting for human use (see, e.g., MRC 2010). However, serious issues of water quality occur in all the deltas, associated with high population density and inadequate treatment of sewage and industrial effluent downstream of the major cities. Fertilizer, pesticide and herbicide inputs from agriculture are significant in the Chao Phraya, Red and Mekong deltas; some aquaculture practices are highly polluting; and intrusion of seawater in the dry season and acid sulfate drainage from poorly managed pyritic soils affect large areas in all the deltas (see, e.g., MRC-VNMC 2004). Levels of agricultural pollutants in most other areas are low, though high concentrations may occur in some places during the dry season as a result of unregulated use of pesticides and fertilizers. Irrigation-induced salinity affects parts of NE Thailand and Central Lao PDR, exacerbated by saline groundwater (Eastham et al. 2008). Soil erosion is widespread in both the plains and uplands, with associated problems of stream water quality and sedimentation (UNDP 2006). Traditional swidden systems have low to moderate overall soil loss (high in cultivated years, low in fallow years), but decreased fallow periods and changes in cropping systems can result in serious erosion under extreme rainfall events (Valentin et al. 2008).

Groundwater

Groundwater use in agriculture varies across the GMS but is generally not extensive. In much of the region, groundwater is used to supplement surface water supplies, or in areas remote from surface water resources. Groundwater consumption is more prevalent during the dry season and in low rainfall years.

In Thailand, groundwater is used for irrigation as a substitute for surface water during the dry season, particularly in the Central Plain and parts of the Chao Phraya Delta. In the Lao PDR, groundwater offers a vast resource but there is no known groundwater-based irrigation development as yet (World Bank 2006). In Cambodia and the Mekong Delta in Vietnam, groundwater is used primarily for small-scale irrigation of vegetables and fruit trees; but in the Central Highlands of Vietnam, groundwater provides the major source of irrigation for the commercially important coffee crop.

Groundwater resources in the Mekong River Basin have not been assessed comprehensively, but it is thought that it has a large untapped potential (MRC and UNEP 1997; MRC 2003; Eastham et al. 2008). Recharge rates are high in most of the region, and particularly within the major alluvial plains and deltas (Figure 3) where

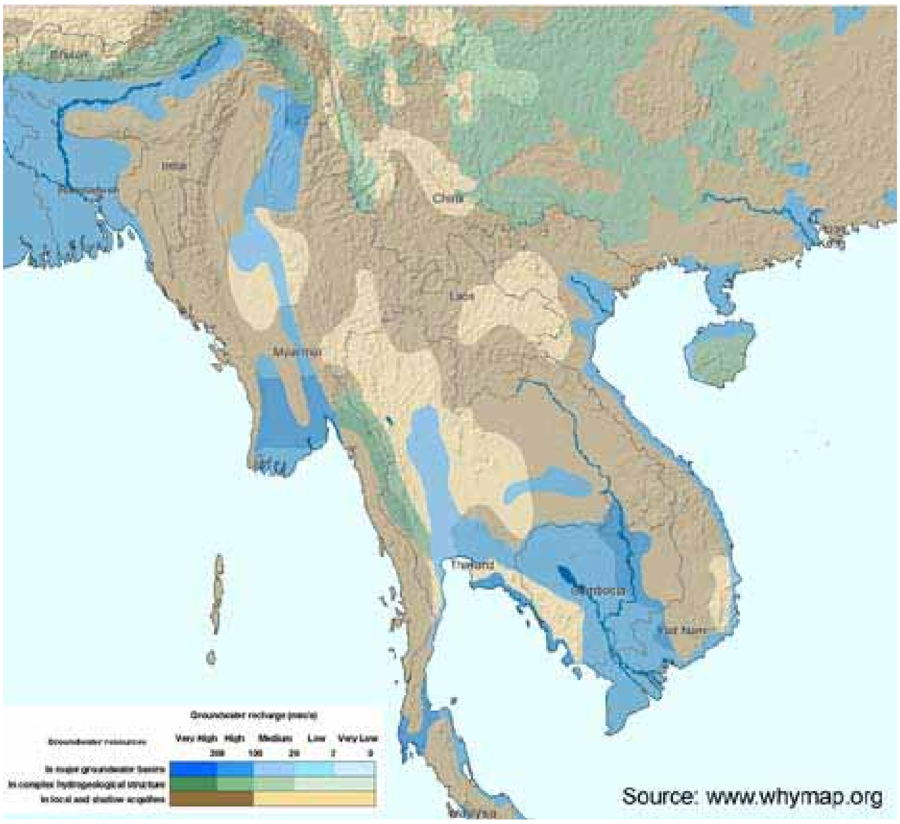


FIGURE 3. Groundwater recharge in the GMS (www.whymap.org).

recharge from rainfall is enhanced by seepage from areas inundated by seasonal flooding. In Thailand, the reserves of freshwater in the major sedimentary aquifers are large: in the Chao Phraya Basin alone, the estimated reserves are 13 km^3, with an estimated safe yield of 3 km^3 (World Water Assessment Programme 2006), In Lao PDR, the groundwater reserves are considered a large and largely untapped resource, particularly for the limestone aquifers in the central region (WEPA n.d.a) but quantitative estimates are not available. Myanmar has an estimated groundwater resource of 495 km^3 (Naing 2005), with the largest potential resources in the Irrawaddy Delta and in the plains of Sagaing Province (UNDP 2006). For Vietnam, the total potential exploitable reserves are estimated to be around 60 km^3/year (WEPA n.d.b). The availability varies from abundant resources in the confined aquifers of the Mekong River Delta to somewhat limited resources in the North-Central Region. The reserves for Cambodia are estimated to be 18 km^3 (Sinath 2001).

The deltas are characterized by surficial aquifers overlying multiple sequences of confined aquifers with variable yields and water quality. In the Chao Phraya Delta, for example, the Bangkok aquifer has eight confined aquifers underlying the surficial aquifer, is over 400 m thick and constitutes a major resource (Ramnarong and Buapeng 1992) with usage in 2005 at 1.5 m^3/day. The aquifers underlying the Irrawaddy Delta are thought to be some of the thickest alluvial artesian sequences in the world (up to 1,800 m in depth) (UNDP 2006). The surficial aquifers in the deltas and floodplains are typically closely linked to, and seasonally recharged by, the rivers. For example, Raksmey et al. (2009) showed that groundwater in the Mekong floodplain is closely coupled with the rivers, which act as both a gaining and losing stream at different locations and seasons; and CIAP (1999) found that groundwater levels up to 30 km each side of the Bassac River closely follow water levels in the river.

Alluvial and deltaic basins composed of relatively recent sediments are vulnerable to developing groundwater arsenic problems (WHO 2008), and naturally occurring arsenic contamination is reported in many of the major deltas in the region. The World Bank (2005) offers an exhaustive review of the occurrence of arsenic contamination across Southeast Asia and South Asia; in Southern Thailand, for example, 25 of 76 provinces are contaminated by arsenic, with average concentrations of 20 mg/l or twice the limit recommended in WHO drinking water guidelines. Groundwater in the Mekong Delta is severely affected by seawater intrusion and acid sulfate soils due to leaching from geochemical processes arising from lowering of groundwater levels (WEPA n.d.a; MRC-VNMC 2004). Point-scale or localized contamination from a range of chemical and microbial constituents is also prevalent in shallow aquifers in some locations as a result of pollution from poorly maintained sewerage infrastructure, landfills, industrial waste and urban areas (Danh 2008).

In the plains and plateaus, local alluvial aquifers of the major rivers often overlie larger regional aquifer systems formed by complex sequences of sedimentary rocks. In the Central Plain of Thailand and central Lao PDR, these include both extensive limestone deposits which constitute major aquifers with yields of 1,000-2,000 m^3/day (WEPA n.d.a) and deposits of gypsum, anhydrite and rock salt. This results in the occurrence of not only naturally saline groundwater unsuitable for drinking or irrigation in some aquifers but also pockets of fresh groundwater suitable for small-scale irrigation (MRC 2005). As an illustration of the extent of the problem, Saraphirom (2009) notes that almost 35% of the Isan Region has salt-affected soils.

Groundwater systems in the uplands are highly variable, characterized by both local fractured rock aquifers with high-quality and low to moderate yields (up to 400 m^3/day), such as those found in the Central Highlands of Vietnam and Bolavens Plateau in Lao PDR. Overexploitation of these systems has resulted in rapid depletion in some areas. In the Central Highlands of Vietnam, for example, groundwater tables have fallen significantly as a result of pumping to irrigate coffee and other crops.

Water, Fisheries and Aquatic Ecosystems

The region contains extensive and diverse wetland ecosystems, comprising riverine floodplains, fresh and brackish-water deltaic wetlands and major lake systems, including Tonle Sap (Southeast Asia's largest freshwater lake), Lake Inle in Myanmar and large upland lakes in Yunnan. Traditionally, wetlands have played an important role in livelihoods, providing fish and other aquatic animals, as well as reeds and a range of food and medicinal plants (MRC 2003). Altogether there are 19 designated Ramsar Convention wetland sites in the GMS (Ramsar 2009).

Food production in the GMS has a high degree of dependence on freshwater ecosystems, which must thus be seen as an integral part of agricultural production systems. Consumption of fish and other aquatic animals is an important part of Southeast Asian diets, and the bulk of consumption is from freshwater sources. Average per capita fish consumption is estimated at 23-45 kg/capita/year, and fish provide between 50 and 80% of the total protein (Hortle 2007; Soe 2008). Studies on the socioeconomics of fish production in the GMS suggest a very high level of participation in fishing, significantly higher than appears in official statistics which do not mention those who fish or farm fish on a part-time basis. For example, a fishery survey conducted in Luang Prabang District in the uplands of Lao PDR (Sjorslev 2000, cited in van Zalinge et al. 2004) revealed that 83% of households reported participation in fishing, mainly for home consumption. Van Zalinge et al. (2004) cite a survey of fishing communities in the Tonle Sap floodplains in Cambodia indicating that 98% of all households reported are involved in some kind of fishing activity throughout the year. A survey conducted in the Mekong River Delta Province of Tra Vinh (where rice farming is considered to be the most important economic activity) noted that 58% of the households reported part-time fishing in the canals, rivers and ponds (Phan et al. 2003). These findings emphasize the importance of the inland capture fishery for small-scale livelihoods and food security.

Fisheries also make an important contribution to the regional economy; estimates of the total value of the Mekong fishery alone are as high as $2 billion per year (Dugan 2008). The fisheries industry accounts for between 4% (Thailand) and 11% (Cambodia) of GDP (Sugiyama et al. 2004; Soe 2008); in Cambodia, this places it ahead of rice production (Starr 2003, cited in Hortle et al. 2004).

There have been dramatic increases in both freshwater and brackish-water aquaculture production since the turn of this decade, with official increases of over 300% in brackish and over 500% in freshwater systems (FAO 2009b; Department of Fisheries, Thailand 2009). Inland freshwater cultivation of finfish (e.g., tilapias, carps, catfish) takes on a diversity of practices (e.g., pond, cage, pens) using land and water areas all over floodplain and plateau areas; and in some cases this cultivation is integrated into farming systems (rice-fish culture, integrated agriculture-aquaculture). Commercial cultivation of brackish water species (prawns, euhayline finfish), mainly for export, has expanded rapidly in the Mekong, Chao Phraya and Irrawaddy deltas, resulting in clearing and conversion of marshes and mangroves, and in water pollution and encroachment on to agricultural land (Gowing et al. 2006). Aquaculture depends on the capture fishery for stocks and feed.

Official statistics indicate that the overall freshwater catch in the region increased between 1990 and 2000 (FAO 2009b), and there is no evidence of a decline since then. In fact, both Thailand and Myanmar have reported significant increases in actual production in recent years. Myanmar has reported a 65% increase in production over 5 years from 1998 to 2003 (FAO 2009b), purportedly achieved through environmental restoration and rehabilitation, restocking floodplains and improved governance (Coates 2002). Statistics on fisheries are notoriously unreliable, and interannual variability is high, so that establishing firm trends is difficult.

However, there is a common perception that the region’s inland fish catch is declining; there is also a high degree of concern regarding the sustainability of the capture fishery. The perception of decline is related mainly to a significant (40-50%) decrease in catch per fisher as the total population and the number of people engaged in fishing have increased (Baran 2005). Concerns about sustainability remain, as there is evidence that large and medium migratory species have declined compared to small migratory and nonmigratory species, and the average size of these small fish has also declined, a pattern typical of overfishing (Hortle et al. 2004). Ten of Cambodia’s freshwater fish species are now listed as endangered (Baran 2005).

Changes to river flow regimes, loss of habitat and disruption of migratory paths pose significant risks to inland fisheries in the GMS. The fish catch is strongly dependent on the extent, duration and timing of flooding, and access to productive floodplain and wetland habitats for feeding (van Zalinge et al. 2004; Krittasudthacheewa and Apirumanekul 2008). Increasing areas of the floodplain are being cleared or converted to agricultural use: for example, the area of flooded forest around Tonle Sap fell from over 1 Mha in the early 1970s to 0.45 Mha by 1997 (Evans et al. 2004). Infrastructure, such as dykes and roads, disrupts access to the floodplain for spawning and feeding. Proposed development of large-scale hydropower storages (see next section) will modify river flows and flooding regimes and block migratory routes. The ecological impacts of these changes are not well understood, but they are predicted to have potentially serious consequences for the fishery.

The freshwater capture fishery is critical to food security and livelihoods of rural communities, as well as supporting commercial-scale operations in the Tonle Sap fishing lots of Cambodia (Hortle et al. 2004; Sithirith and Mathur 2008). Sustainability of freshwater fisheries is inextricably linked with water resources management, and protection of the ecological systems that sustain the fishery is an important regional priority.

Hydropower

The GMS has estimated potential hydropower resources of over 200,000 MW (Box 1). Demand for energy within the region is growing rapidly, and all governments are considering major hydropower developments to meet part of that demand. A review of hydropower in the GMS (King et al. 2007) compiled an inventory of 82 projects existing or under construction and a further 179 planned and proposed projects. Box 1 and Figure 4 outline the main planned developments within each of the major basins in the region. Hydropower development is considered as a relatively cheap, independent solution for energy demand, and also contributes less greenhouse gas (GHG) emissions than alternatives such as charcoal, oil and biofuel. However, existing and proposed major hydropower development will result in changes to flow regimes and river ecology with significant implications for both agriculture and fisheries.

Many of the proposed projects include considerable storage, and so have the potential to modify river flows significantly. For example, current development in the Mekong provides a storage of around 12 km^3 (2.5% of total annual flow); Hang and Lennaerts (2008) estimate that, under a “definite future” scenario, this will increase to 44 km^3 and under “full development” to more than 75 km^3 (16% of total annual flow). A preliminary assessment of the hydrological impacts of the “definite future” scenario (Hang and Lennaerts 2008) predicts an increase in discharge in the low-flow season of around 50% at Chiang Saen, declining downstream to an increase of only 9-13% at Chau Doc. Accompanying decreases in discharge in the high-flow season are proportionately smaller (15 to 4-7%, respectively). The projected increase in the discharge in the low-flow season is larger than projected irrigation demands from all Lower Mekong countries and could provide significant opportunities for irrigation development and for mitigation of current dry-season shortages and saline intrusion in the delta.

The ecological consequences of such large changes are not well understood but there are potentially large impacts on wild fish populations. Fish recruitment patterns are strongly influenced by hydrological processes that trigger the timing of spawning and affect fecundity rates, larval survival rates and food availability. Very little is known of the biology and ecology of the diverse species and differences in how they respond to these changes. Empirically, it has been observed that exploitable biomass in fisheries is more sensitive to dry, than flood-season, conditions (Halls et al. 2001), so fisheries are vulnerable to decline in dry-season flows. There are specific concerns that changes to the flow regime could impact negatively on the ecology of the Tonle Sap system, which underpins two-thirds to three-quarters of the inland capture fisheries of Cambodia (Baran 2005). At Kratie, upstream of the confluence with the Tonle Sap, dry-season flows are projected to increase by 20-30% and wet-season flows to fall by 4-8% (Hang and Lennaerts 2008). Kummu and Sarkkula (2008) concluded that relatively small rises in the dry-season level would permanently inundate a disproportionately large area of the floodplain, threatening the gallery forest; and that a smaller flooding amplitude would decrease ecosystem productivity. Changes in the pattern and timing of flooding are also likely to disrupt physiological cues for fish migration.

Blockage of fish migration paths by dams has serious impacts on recruitment and spawning (van Zalinge et al. 2004; Thanh et al. 2004). A high proportion of fish species in Southeast Asian rivers are migratory, with seasonal movements over large distances to access spawning and feeding grounds (Baran 2006); Dugan (2008) reports that up to 70% of the Mekong fishery depends on long-distance migrant species. Halls and Kshatriya (2009) investigated the impact of barrier effects of proposed Mekong mainstream dams on fish populations using population dynamic models, and concluded that structures would need to pass at least 60-87% of upstream migrating adults to maintain viable exploited populations. These estimates were even higher for larger species, or if multiple dams were included in the analysis. They comment that *“We were unable to find evidence in the literature to suggest that the necessary rates of upstream passage success to sustain even the small species summarized above have been* *achieved elsewhere."* Mainstream dams thus pose a significant threat to the viability of migratory fisheries, and it is essential that these impacts – and their economic and social consequences – are taken into account in feasibility and impact studies.

Large dams trap sediment carried by rivers and can significantly reduce suspended sediment load and delivery of sediment to downstream areas. Removal of sediments results in geomorphological changes in the river (increased bed scour, channel and bank erosion) and decreased ecosystem productivity in the floodplain (since nutrients are carried with sediments). Kummu and Varis (2007) estimate that the major Chinese reservoirs on the Upper Mekong (Lancang) will have sediment trapping efficiencies of 66-92%, with large potential impacts on downstream areas.

Box 1. Existing and proposed hydropower development in GMS basins

Mekong: The Mekong River Commission lists 23 existing large and small dams, 13 under construction and up to 80 planned or proposed in the Lower Mekong, including 11 proposed dams on the mainstream Mekong. The combined live storage of existing large dams in the Lower Mekong Basin is about 9.6 km^3; of the dams planned and under construction it is 44 km^3. This is in addition to a cascade of eight dams on the Lancang (Upper Mekong) of which two are complete and three under construction – these include the Xiowan and Nuozhadhu dams with a combined live storage of 22,200 million m^3 (MRC 2009a). These bring the total live storage of the whole Mekong to 75.6 km^3, about 16% of the total discharge of 475 km^3.

Red River: Currently there are two operating hydropower projects, with another four proposed (ADB 2009c), in addition to a total of 27 existing and planned small dams for irrigation (Water Resources eAtlas 2003).

Chao Phraya: There are three operating dams for hydropower and irrigation with no additional dams planned.

Yangtze: A series of eight dams are planned on the Upper Yangtze in Yunnan (upstream of the Three Gorges Dam), including a controversial proposal for a dam at Tiger Leaping Gorge (IRN 2009a).

Salween: In 2006, the Thailand and Myanmar governments signed an agreement to build the Ta Sang Dam, the first of a cascade of five large dams on the Salween. Plans for a cascade of 13 dams in the Upper Salween (Nu) in China have apparently been shelved (IRN 2009b).

Irrawaddy: Two dams are currently under construction, including the Myitsone Dam being built in cooperation with China, one of seven hydropower developments planned for the Irrawaddy (Irrawaddy 2009).

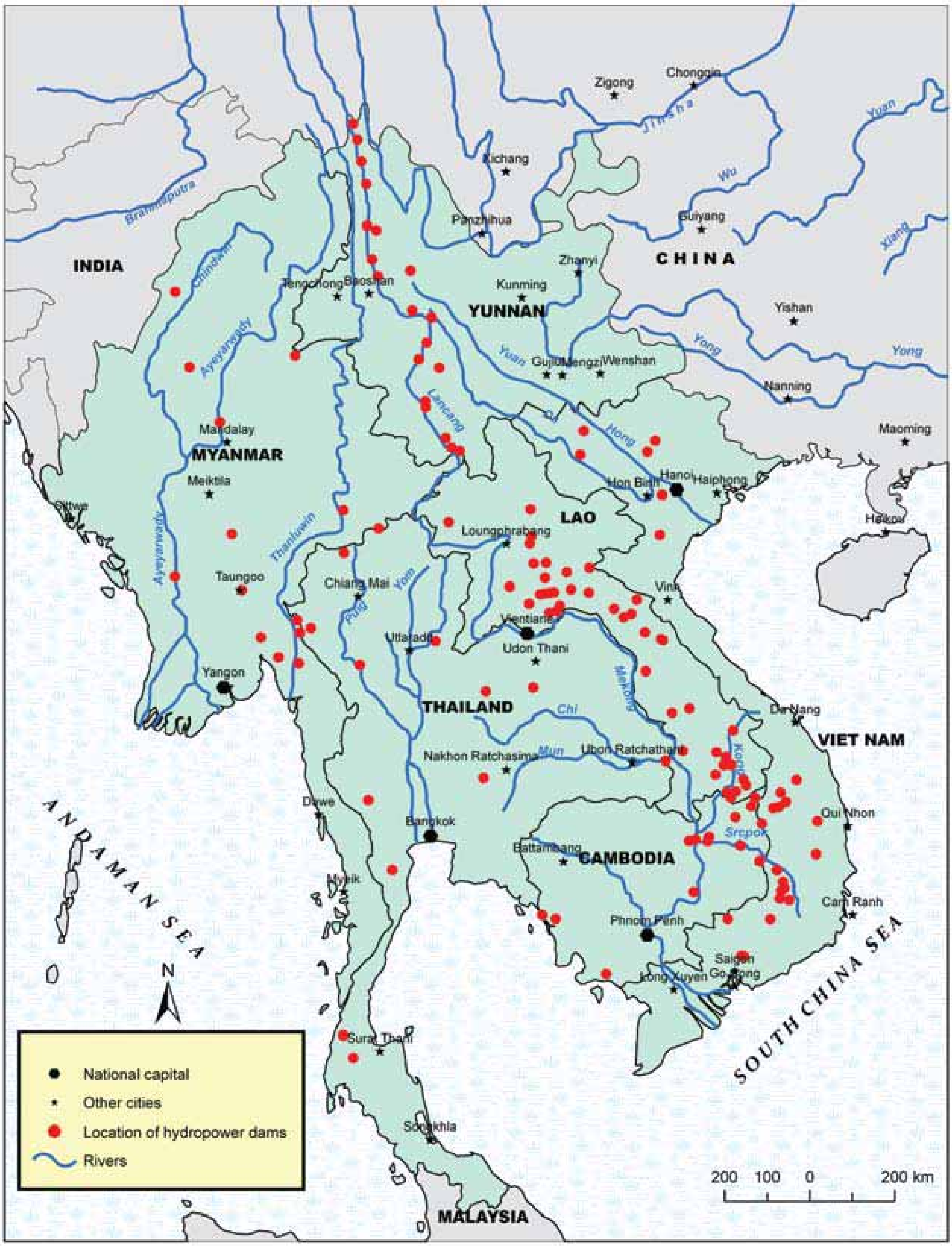


FIGURE 4. Current and proposed hydropower development in the GMS (data are from ADB 2009c).

Climate Change in the GMS

Climate change analyses have been undertaken in Southeast Asia for different purposes:

- Characterizing likely future climate changes (Ruosteenoja et al. 2003; Snidvongs et al. 2003; Mac Sweeney et al. 2008a, b, c).
- Projecting future river discharge and water level 2009).
- Assessing vulnerability (Anshory-Yusuf and Francisco 2009).
- Proposing recommendation for mitigation and adaptation (Eastham et al. 2008; TKK and SEA START RC 2009).

All have been based on climate scenarios developed for the International Panel on Climate Change (IPCC) Special Report on Emissions Scenario (SRES) (IPCC 2000), and in some cases downscaling of general circulation models (GCMs) to regional scale (e.g., Snidvongs et al. 2003; TKK and SEA START RC 2009). As part of this study, an analysis was carried out by IWMI of observed (1953-2004) and projected (1960-2049, using PRECIS climate model) rainfall and temperatures in the region, to identify climate trends. The results of these studies are summarized in Table 3 and analyzed in more detail in the sections below.

Based on the results of studies in the region by IWMI and others, anticipated climate changes in the GMS to 2050 can be summarized as follows:

- Increase in temperature of 0.02–0.03 °C per year across the entire region in both warm and cold seasons, with higher rates of warming in Yunnan and northern Myanmar.
- Higher temperatures will increase evapotranspiration, increasing the water demand of crops and pastures in both rain-fed and irrigated systems. Irrigation demand in semiarid regions of Asia is estimated to increase by 10% for each 1°C (Fischer et al. 2002).
- No significant change in annual rainfall across most of the region (projected changes in rainfall vary from decreases of a few millimeters per year to increases of up to 30 mm, with a high degree of uncertainty).
- Some (small) seasonal shift in rainfall, with drier dry seasons, and in some studies shorter, more intense wet seasons so that even if total annual rainfall does not change significantly, it is possible that the availability of water for agriculture may change, with increases in the incidence of both droughts and floods.
- Sea level is expected to rise 33 cm by 2050 (MONRE 2008) in addition to an observed rise of 20 cm over the last 50 years (Hien 2008).
- Increase in temperature of sea surface may increase the intensity and incidence of typhoons during El Niño years (MRC 2009b).

To date, only the increases in temperature and sea level have been observed. An analysis of historical rainfall records indicates a high degree of variability, but no trend in either overall amount or seasonality of rainfall. This contrasts with the widespread perception, reflected in a number of recently published reports (e.g., ADB 2009a; WWF 2009) that climate change is already being felt in the region as increases in the incidence and severity of extreme climate events. This perception is a result of confounding climate change with climate variability (or sometimes even with land use change). For example, ADB (2009a) quotes Mekong floods in 2000 and droughts in Lao PDR and Vietnam in 1997 and 1998 as examples of extreme events attributed to climate change. However, there is no convincing evidence that these events are outside of the range of “normal” climate variability, or that the frequency of such events has increased, at least in the mainland Southeast Asia (this study; MRC 2005). In the Mekong Delta, the reported increase in flood damage can be attributed to demographic and land use changes, as increasing population has resulted in settlement of areas previously not used precisely because of their vulnerability to floods.

There is a high level of uncertainty associated with rainfall projections, particularly in the period to

TABLE 3. Comparison of projected climate changes from different studies.

Authors	Snidvongs et al. 2003	Hoanh et al. 2003	Ruosteenoja et al. 2003	TKK and SEA START RC 2009	Eastham et al. 2008	Mac Sweeney et al. 2008 a,b,c	ADB 2009a	This study
Location	Lower Mekong catchment	Mekong Basin	Southeast Asia	Lower Mekong catchment	Lower Mekong catchment	Cambodia, Vietnam	Thailand, Vietnam	GMS
Models	CCAM	HADCM3	7 GCMs	ECHAM4-PRECIS	11 GCMs	15 GCMs	MAGICC (GCM)	PRECIS/ECHAM4
Scenarios	Not specific	A2, B2	A1F1, A2, B1, B2	A2	A1B	A2, A1B, B1	A1F1, B2	A2, B2
Period	From [1×CO_2] to [2×CO_2]	1960-2099	1961-2095	1960-2099	1976-2030	1970-2090	1990-2100	1960-2049
Projected changes in annual rainfall	Not explicitly quantified	-1.64 mm/yr to +4.36 mm/yr	Either >0 or <0, depends on models and scenarios. Almost always insignificant	Increase (not explicitly quantified)	+0.1 mm/yr to 9.9 mm/yr	+0.3 mm/yr to +0.6 mm/yr	1990-2050: +1.26 mm/yr to -1.62 mm/yr (B2); 0.66 mm/yr to -1.14 mm/yr (A1F1) 1990-2100: +3.27 mm/yr to +4.91 mm/yr (A1F1) and -1.63 mm/yr to -2.45 mm/yr (B2)	No significant change at the whole GMS scale
Changes in seasonal rainfall pattern	Dry season drier and longer Wet season delayed by 1 month		Dry season drier and longer Wet season delayed by 1 month	Dry season drier and longer Wet season delayed by 1 month	Wetter wet season (+1.7 to +6.1 mm/yr) Drier dry season (-0.3 mm/yr; not significant)	Wetter wet season : +0.8 to +1.5 mm/yr (KH); +0.4 to +1.5 mm/yr (VN) Drier dry season: -0.7 to -0.1 mm/yr (KH); -0.3 to -0.1 mm/yr (VN)		Wetter wet season in North Mynamar and Gulf of Thailand (From +0.2 to +0.6 mm/yr) Drier dry season on both sides of Gulf of Thailand (-2.5 to -2.8 mm/yr)
Temperature	+ 1°C to +3°C (over a 100-yr period)	+0.026 °C/yr to +0.036 °C/yr	+0.01 °C/yr to +0.05 °C/yr	Increase (not explicitly quantified)	+0.012 °C/yr to +0.014 °C/yr	0.00 °C/yr to +0.06 °C/yr	+0.03 °C/yr to +0.06 °C/yr	+0.023 °C/yr to +0.024 °C/yr

2050. In addition, the rise in CO_2 emission during 2000-2007 was higher than that in the worst-case scenario analyzed by the IPCC (IPCC 2007), and global warming may accelerate much more quickly than current models indicate (GCP 2008). Changes beyond 2050 have not been analyzed in this study, which focuses on impacts in the short to the medium term. Global studies (IPCC 2007) suggest that rise in temperature will become nonlinear and much more rapid, and that rainfall will increase. Impacts due to climate change by 2100 are projected to be correspondingly much more severe (ADB 2009a).

Given the high degree of uncertainty around projections of rainfall and runoff, it is counterproductive to use them as the basis for adaptation planning until more consistent estimates are available. It is more useful to characterize likely change as an increase in the variability and uncertainty of water availability and to take a “no regrets” approach to water management, with actions to improve both water use productivity and access to on-farm and off-farm storage, and to reduce water-related risks.

Temperature and Precipitation

Most of the studies on climate change undertaken in the GMS have attempted to quantify the impact of global warming on the regional climate by comparing mean annual temperature and rainfall averaged over successive periods whose length generally varies from 10 to 30 years. For instance, Mac Sweeney et al. (2008c) examined potential change in rainfall and temperature time series in Southeast Asia by comparing averages from a baseline period (1970-1999) with mean projected values for the 2030s, 2060s and 2090s. Ruosteenoja et al. (2003) calculated changes in seasonal surface air temperature and precipitation in Southeast Asia between a baseline period (1961-90) and three 30-year periods centered on the 2020s, 2050s and 2080s. However, caution must be used in quantifying climate changes using this approach. The analysis of three 52-year (1953-2004) time series of rainfall observations in Thailand, undertaken as part of this study, indicates that differences between 10-year and 30-year means can reach 30 and 12%, respectively, whereas no long-term monotonous trend was observed in the three time series. Thus these changes cannot be attributed to climate change, but rather reflect natural multidecadal climate variability.

In order to better distinguish natural climate variability from climate change in the GMS, this study applied a rank-based statistical test designed to detect monotonous trends in annual time series of rainfall and temperature variables derived from daily projections produced by the PRECIS regional climate model over the period 1960-2049 under the SRES scenarios A2 and B2[2] (IPCC 2000). Providing Regional Climate for Impact Studies (PRECIS) (Jones et al. 2004), a regional modeling system developed by Hadley Center, UK, provides data at a spatial resolution of 0.2° x 0.2°, which is appropriate for regional climate studies, compared to an order of magnitude of coarser resolutions provided by GCMs. PRECIS was applied to the GMS by the START (SysTem for Analysis, Research and Training) Southeast Asia Regional Center, using the output from ECHAM4 GCM[3] (Roeckner et al. 1996). Fourteen annual climate variables were derived from these daily rainfall and temperature series to describe regional climate, including cumulative rainfall depths per year, per season and per range of daily rainfall; timing of the rainy season; minimum, average and maximum temperature; and intra-annual distribution of the temperature values. The statistical test was applied to annual time series of each climate variable at 2° x 2° spatial resolution to detect

---

[2] A2 and B2 are two climate change SRES scenarios studied by IPCC. A2 corresponds to a storyline of high population growth with slower per capita economic growth and technological change, and B2, a storyline of moderate population growth and economic development with less rapid and more diverse technological change.

[3] ECHAM4 GCM is a model based on the prevision model of the European center "European Centre for Medium Range Weather Forecast" (ECMWF) and modified by the German modeling center and the Max Planck Institute to adapt it to the long-term climatic simulations.

possible monotonous changes significant at the 95% confidence level.

Some outcomes of this analysis are presented in Figure 5. Temperature increases over the entire GMS during the period 1960-2049 in both cold and warm seasons (+0.023 °C/year). The highest rates of temperature increase (+0.035 °C/year) are anticipated in the northern parts of the GMS (north Myanmar and north Yunnan) and the lowest rates correspond to maritime areas (+0.016 °C/year). For the same period annual rainfall increases in Myanmar and in the Gulf of Thailand from +23 to +55 mm and from +341 to +693 mm, respectively, and rainfall decreases in central Vietnam and southern Lao PDR from 0 to -189 mm, and in the Andaman and South China Seas from -204 to -402 mm. In general, increases of annual rainfall are due to increases of heavy rainfall during the rainy season, and the decreases in rainfall are explained by a reduction of light rains during the dry season. Time-lags in the seasonal patterns mostly result in a slight delay at the onset, the peak and the end of the rainy season. From 2009 to 2049, these delays range from 0.1-0.4 day in the northwest of the GMS to 3.8-7.1 days in the southeast. Most of these results are consistent with those from Snidvongs et al. 2003, Mac Sweeney et al. 2008a, b and Ruosteenoja et al. 2003. However, the spatial extent of the areas which experience rainfall changes is smaller in the present case. This discrepancy is probably due to the differences in the length of the study periods (which are deliberately shorter in the current study since it targets the short- to medium-term changes), methods used to detect changes (the rank correlation test only detects significant changes within a specific confidence interval) and the use of distinctive climate models.

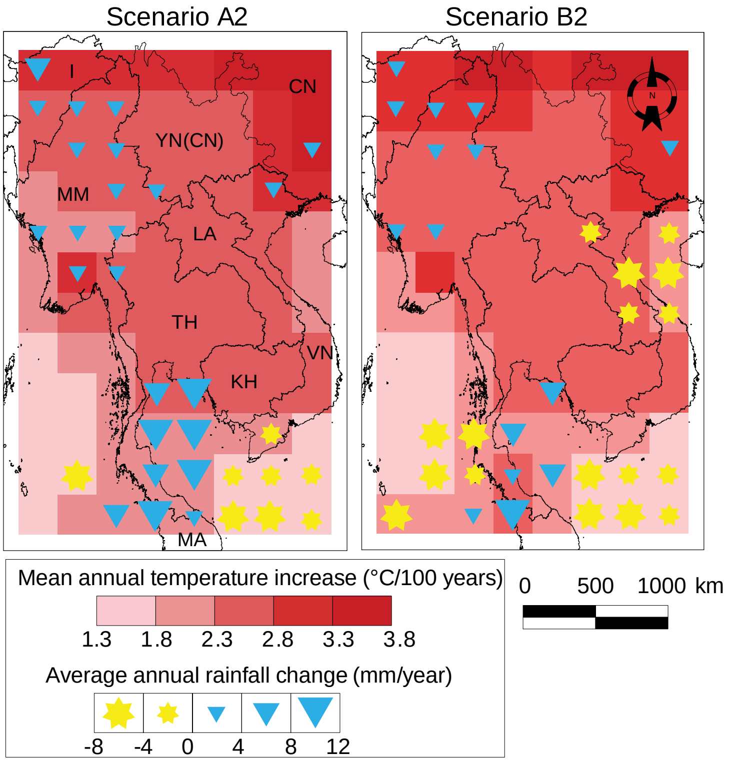
Projections of future climate in the GMS from different studies are compared in Table 3. While there is a degree of consistency in projections of future temperature trends, there are significant discrepancies between projections of rainfall changes in different studies, and clear trends cannot be identified. This is particularly marked for the first half of the twenty-first century, e.g., model estimates reported by TKK and SEA START (2009) indicate that precipitation will fluctuate in the first half of the century, and there were differences between the estimates derived from the A2 and B2 scenarios.

Accelerated Melting of Glaciers

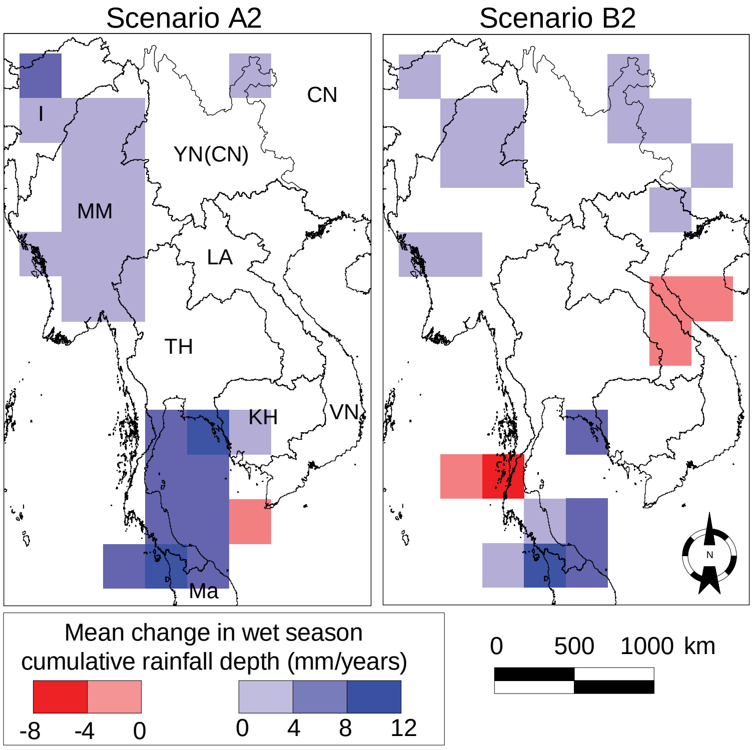
Three rivers within the GMS originate from the melting of glaciers: the Mekong, the Irrawaddy and the Salween. Eastham et al. (2008) calculated that the total volume of the glaciers within the Mekong catchment is about 17.3 km^3. This estimation was based on data provided by the World Data Center for Glaciology and Geocryology and did not take into account the permafrost covering about 50,000 km^2 of the Tibetan part of the catchment (IUCN et al. 2003b). With an average soil porosity of about 10% and a maximal 2 m depth of frozen soil, this permafrost would represent about 10 km^3 of ice. In total, 27.3 km^3 of ice is equivalent to 25.0 km^3 of water. Assuming that all glaciers and permafrost will have totally disappeared by 2030 as a consequence of global warming (an extreme scenario), and that the melting occurs at a constant rate only during the six warmest months of the year, the glacier melting would generate a discharge of about 80 m^3/s from April to September. This value is negligible when compared to the mean discharge of the Mekong River recorded at Chiang Saen (China border) during this period of the year (3,500 m^3/s). Even if the estimated melting rate was 100% underestimated, the glacier melting would still remain insignificant.

The surface area of the high-altitude wetlands (IUCN et al. 2003a, c) and the spatial covering of the glaciers (National Snow and Ice Data Center of the Colorado University) in the Irrawaddy and Salween catchments are both much smaller than in the Mekong catchment. The contribution of ice melt to the mean discharge of the Irrawaddy (13,500 m^3/s) and Salween rivers (1,500 m^3/s) is equivalent to essentially 0 and 9%, respectively (Jianchu et al. 2007).

The impact of the glacier-melting is thus negligible in the two main catchments of the GMS (Mekong and Irrawaddy). The situation may slightly differ in the Salween catchment where the



a) Annual temperature and rainfall change over the period 1960-2049.



b) Changes in wet-season cumulative rainfall depths over the period 1960-2049.

FIGURE 5. Projections of impacts of climate change in GMS.

ice-melting contribution to total runoff is higher, but the population that would be potentially impacted by such changes represents only 2% of the total population of the GMS.

Rise in Sea Level

Global mean sea level has risen by 1.7 mm per year over the last century. During 1993-2003, the rate increased to 3.1 mm per year, but it is not clear whether this is due to decadal variability or to an increase in the long-term trend (Bates et al. 2008). In Vietnam, Hien (2008) reports an observed rise of 20 cm over the last 50 years while Chaudhry and Ruysschaert (2007) report a rate of around 2 mm a year. Rise in sea level in the deltas is exacerbated by land subsidence due to groundwater extraction and sediment loss. Ryvitski et al. (2009) report relative rises of sea level of 6 mm per year in the Mekong Delta and 13 to 150 mm per year in the Chao Phraya Delta.

Rise in sea level is expected to accelerate with global warming. An additional rise of 33 cm is expected on the Vietnam coast by 2050 (MONRE 2008), and levels are projected to reach at least 1 m above current levels by 2100 (GCP 2008; IPCC 2007) posing a significant threat to the deltas and coastal regions. Wassmann et al. (2004) predict that a rise of 20-45 cm will seriously aggravate flooding in the Mekong Delta, with impacts in all three seasons of rice cropping. Dasgupta et al. (2007) estimate that more than 5% of Vietnam's total land area and 10% of population would be affected by a rise in sea level of 1 m, with 5,000 km^2 of the Red River Delta and 15,000-20,000 km^2 of the Mekong River Delta being flooded. The Red, Chao Phraya and Irrawaddy are steeper deltas, and so less prone to a rise in the sea level; Dasgupta et al. (2007) estimate that a 1 m rise in sea level would have smaller but still significant impacts, affecting 1-2% of both total land area and population. These projections do not take into account the impacts of storm surge or salinity intrusion. While the more severe impacts of the rise in sea level will not be felt until after 2050, it is essential to take longer-term impacts into consideration in planning and investment.

Water Availability

Translating changes in rainfall into changes in availability of surface water and groundwater depends on a complex set of hydrological factors. Hydrological models to translate climate change impacts into changes in flow are not available for river basins in the GMS, with the exception of the Mekong. In large river basins, small changes in precipitation can accumulate to significant changes in flow. For example, Eastham et al. (2008) modeled hydrological impacts of climate change in the Mekong to 2030 and, based on the assumption of an average increase in rainfall of 0.2 m (13%), projected a 21% increase in overall flow in the river and an increase in probability of "extreme wet" flood events from 5% under historical conditions to 76% under future climate conditions. Such projections are specific to the input of the climate scenario, including both the volume and timing of rainfall, and to other assumptions including land use, but the results illustrate the magnifying effect that hydrological conditions can have on climate impacts.

Attempts to quantify potential flow changes in the GMS have been made only in the Mekong Basin, where several studies have estimated river flows under different climate scenarios (e.g., Eastham et al. 2008; TKK and SEA START RC 2009; Hoanh et al. 2004; Kiem et al. 2008). TKK and SEA START RC (2009) compared results from these studies and found general agreement that rainy-season precipitation, runoff and discharge will increase in the first half of the twenty-first century, although there were significant differences in projected magnitudes of changes in water level and flooded area. However, estimates for dry-season changes differed, with projections of both increased and decreased flow in dry-season months. A recent study of the projected changes in floods and droughts globally to 2100 (Hirabayashi et al. 2008) indicated that the incidence of flooding in the

Mekong is not likely to increase, despite an overall increase in annual flow but that the number of drought days will increase. Results presented graphically for the rest of the region indicated significant variations across the region, with no clear regional trend. Studies are underway to improve estimates of hydrological impacts of climate change in the Mekong (e.g., current collaborative projects between MRC and IWMI; MRC and CSIRO; and the Water and Development Research Group of Helsinki University and Southeast Asia START Regional Center).

Higher temperatures will increase evapotranspiration, thus increasing the water demand of crops and pastures in both rain-fed and irrigated systems. Irrigation demand in semiarid regions of Asia is estimated to increase by at least 10% for each 1°C rise in temperature (Fischer et al. 2002). Livestock demands per head will also increase. Increased water use by crops and pastures will impact on the availability of water for environmental and other uses. Changes in timing of the wet season could also affect irrigation demand (either positively or negatively, depending on the crop calendar) and impact on crop yields. For example, Hasegawa (2006) reports that in Northeast Thailand, rice transplanted early gives a substantially higher yield than that transplanted later.

Global projections indicate that the incidence of extreme climate events is likely to increase (IPCC 2007). Vietnam is one of the ten countries worldwide most at risk to tropical cyclones (Chaudhry and Ruysschaert 2007). These cyclones are responsible for a significant component of annual rainfall (MRC 2005), and changes in the patterns of storm activity could impact on rainfall and runoff distribution. During the recent storm Ketsana in September 2009, damage due to flooding was more serious than actual storm damage, not only along the Vietnam coastal zone but also in the highlands of Cambodia, Lao PDR and Vietnam.

Climate Change in the Context of Other Drivers of Change

A combination of population growth and rising living standards is posing a new set of challenges in meeting future food demand in the GMS, and economic development is placing increasing pressure on land and water resources. Global markets are driving changes in agricultural production to meet export demands, and have opened up external sources of capital for investment in agriculture and infrastructure. China's economic growth and reemergence as a major trading partner is placing an ever-increasing demand on the natural resources of the region (Rutherford et al. 2008). Increased energy requirements are driving large hydropower developments which will impact on freshwater ecosystems and water availability for agriculture. All these trends have implications for water management, but two forces are currently reshaping water and land management in the GMS at an unprecedented rate: population growth, and investment and trade.

Population Growth

The population in the GMS is projected to grow from its current level of 275 million to reach over 340 million by 2050 (World Gazetteer 2009; World Bank 2009a; Figure 6). Thus, based simply on population growth, if no new land is brought into production, a 25% increase in average per hectare productivity will be needed simply to maintain current levels of per capita food production. This could only be achieved with significant increases in irrigation, placing heavy additional demands on water resources. Alternatively, to hold the current ratio of land per capita constant would require an additional 7.2 Mha of arable land

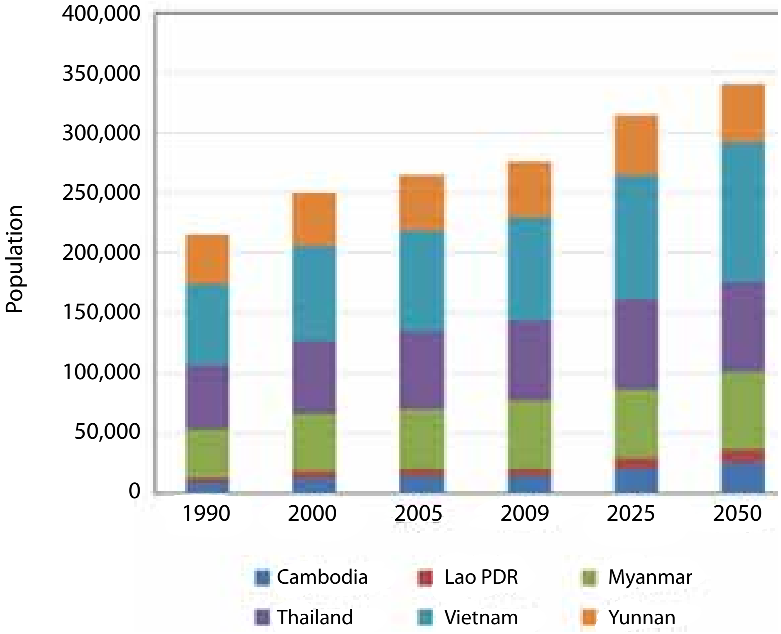


FIGURE 6. Population growth in the GMS, 1990–2050.

(see Table 4, FAO 2009b), again, inducing large increases in water demand. Such increases in agricultural water demand are likely to come at the expense of flows for the environment, and will place significant pressure on ecosystems and biodiversity.

Changes in diet and globalization of food markets mean that the picture is much more complex. As incomes increase, there is a general trend common across the world to more diversified diets with a higher proportion of food from animal sources and high-value fish, a shift from cereals to noncereals, and an increase in consumption of high-value foods such as fruit, sugar and edible oils (Pingali 2004). These trends are observed across Southeast Asia, although cultural and regional differences are pronounced, e.g., Thailand consumes significantly less animal products than China, even with much higher GDP. Changes in dietary preferences have significant implications for food production systems: a more meat-based diet requires a much higher level of resource inputs, including water (CA 2007).

Investment and Trade

Agriculture in the GMS is transforming in response to global markets, directly through investment in agribusiness, and indirectly, as export markets (particularly in China) influence production trends. International demand for commodities such as rubber, cassava, sugarcane, corn, palm oil, cashew, coffee, pepper and eucalyptus has driven a large shift in production, with an increase in commercial plantations and contract cropping. Governments in Lao PDR and Cambodia are promoting commercialization and industrialization of agriculture, and seeking private investment (foreign and domestic) to fund the transition.

This has resulted in an upsurge of investment in plantation agriculture which is profoundly altering agricultural production, with a rapid rise in planting commercial (often nonfood) crops such as rubber, oil palm, grains and legumes for feed stocks. In Lao PDR, direct foreign investment in agriculture between 2001 and 2007 totaled $665 million, with a huge influx of $458 million

TABLE 4. Area of arable land per capita and as a percent of total land area (1990–2050).

	1990 Arable land			2007 Arable land			2050 Arable land	
							Area of arable land constant	Area per capita constant
	1,000 ha	ha per capita	% of total land area	1,000 ha	ha per capita	% of total land area	ha per capita	1,000 ha
Cambodia	3,695	0.38	20	3.800	0.26	21	0.15	6,606
Lao PDR	799	0.20	3	1.170	0.20	5	0.13	1,855
Myanmar	9,567	0.24	14	10.577	0.22	16	0.18	12,729
Thailand	17,494	0.32	34	15.200	0.24	30	0.23	16,044
Vietnam	5,339	0.08	16	6.350	0.07	19	0.05	8,948
Yunnan	-	-	-	2.381*	0.05	6	0.05	2,541
China	123,726	0.11	13	140.630	0.11	14	0.10	150,097

Sources: FAO 2009c; World Bank 2009a; World Gazetteer 2009.

* Assumes 6% of Yunnan is arable (UNEP TEI 2007).

in 2006 (Rutherford et al. 2008). Similarly, recent investment flows into Cambodia have been very large: in 2007, $363 million went to agriculture and agroindustry, and land concessions (domestic and foreign) covering a total area of 943,069 ha (15% of Cambodia's arable land) had been granted in 2006 (MAFF 2009a). If realized, these concessions will change the face of Cambodian agriculture, bringing extensive new areas into production. The extent of foreign investment in agriculture in Myanmar in the past has been limited (UNDP 2006), but there are recent press reports of Chinese investment in plantations for rubber, palm oil and pulpwood (Associated Press 2009).

Investment is also driving rapid expansion in the mining and energy sectors. Most activity in hydropower in the GMS is funded through foreign investment, except in Vietnam and Yunnan, where domestic and government companies dominate. For example, in Lao PDR and Cambodia, China is currently involved in over 20 hydropower projects either as an investor or developer (Rutherford et al. 2008), with a large number of potential projects in the pipeline (King et al. 2007), and International Rivers (2009) lists over 50 current and proposed hydropower projects in Myanmar funded or built by Chinese companies. International investment has financed the development of large-scale mines in the region: for example, in Lao PDR, the gold and copper mines at Phu Bia (Chinese investors) and Sepon (Australian/Chinese investors), and coal mines in Xayabury (Thai investors).

Recently, extensive deposits of bauxite have been identified in southern Lao PDR, Northeast Cambodia and the Central Highlands of Vietnam. Chinese, Vietnamese and Australian companies, amongst others, have put forward proposals for large-scale extraction and processing. Development of these deposits could have significant impacts on water resources and the environment locally. In addition to water demand for mining and processing, and questions of disposal of the large volumes of "red muds" produced as wastes from processing bauxite, smelting of alumina requires enormous amounts of energy, and the viability of bauxite extraction may ultimately depend on concomitant development of hydropower as an energy source (Lazarus 2009).

Relative Impacts of Different Drivers of Change

Climate change is incremental with small changes from year to year that, initially at least, are within the range of observed natural climate variability and will be masked by them. At this stage, there is no convincing evidence that climate change has yet significantly affected either the availability or distribution of water in the region (see above).

In contrast, social, demographic and economic drivers are already forcing rapid and visible change in the water resources of the GMS. Withdrawals for irrigation regularly cause seasonal water shortages and water use conflicts in some areas (see, e.g., Pech and Sunada 2008; MRC-TNMC 2004). Construction of dams for irrigation and hydropower has significantly changed local downstream flow patterns (e.g., at Nam Theun 2 in Lao PDR; ADB 2004) and productivity of local fisheries (e.g., at Pak Mun in Thailand; World Commission on Dams 2000a).

Quantifying the relative impacts of different drivers of change is not easy, but it is clear the impacts of demographic and economic changes are of at least the same magnitude as, or greater than, the impacts driven by climate change, and will occur in a shorter time span. For example:

- Published projections of climate-induced changes in mean annual flow in the Mekong range from 5% (Hoanh et al. 2003) to 20% (Eastham et al. 2008); planned large hydropower projects in the Mekong are projected to increase dry-season flows by 10-50% and decrease wet-season flows by 6-16% (Hang and Lennaerts 2008).
- Estimates of changes in crop productivity due to climate change are in the range of 2-30% over a 20-30 year period (Eastham et al. 2008; Cruz et al. 2007; Hoanh et al. 2004); in comparison, total agricultural production has increased almost 80% in Vietnam and over 200% in Cambodia over the last 15 years, with even faster growth in specific sectors and regions.
- Dasgupta et al. (2007) estimated that rise in sea level by 1 m would reduce Vietnam’s GDP by 7% and ADB (2009a) estimated reduction of Southeast Asia’s GDP, related to climate change, by 6.7% per year by 2100; the 1997 Asian crisis reduced Thailand’s GDP by almost 10% in 1998 and the current financial crisis is similarly expected to significantly reduce or reverse GDP growth in most countries (World Bank 2009b).

Thus, in the next 20 to 30 years, management of land and water resources will be shaped by a complex mixture of social, economic and environment factors, with impacts of at least the same order of magnitude as, or greater than, direct impacts of climate change. Some, like climate change and population growth, are cumulative while others such as food prices, oil prices, financial crises and political fluctuations can have immediate and severe effects, but these effects fluctuate over time and tend to even out. In the longer term (beyond 2050) climate may become the most urgent driver of change, as rise in sea level – without any adaptation – may force abandonment of significant areas of productive land in the mega-deltas and coastal zones, requiring a radical rethinking of production systems to maintain food sources for the inevitable increase in population.

Water Management Strategies

Water and its efficient use comprise the key to future food security and economic growth in the region. Whilst the region may not be seen as suffering from water scarcity, difficulties in access and dry-season shortages already induce economic water scarcity and conflicts over water use in some areas. Increasing demands from agriculture, urbanization, industrialization, mining and hydropower development will place greater pressure on maintaining flow regimes, water quality and aquatic habitats.

In devising strategies to improve future water management in the GMS, three important issues have to be addressed. The first is to define and quantify the water resource, to understand a) the physical, social, political and economic drivers that determine water availability and access (including transboundary constraints) and b) the ways in which changing water availability and access affect food production, livelihoods and the environment. The second is to improve understanding of the impacts of climate change on runoff, infiltration and water availability. The third is to identify adaptive management strategies and trade-offs to balance changing water availability against increasing demands, in order to cope with uncertainty and change. Key components of adaptive management are water-allocation strategies, development of appropriate water storage, and adoption of key policy instruments providing incentives to use water differently. Clearly, all of the above will require significant financial investments and a commitment by policymakers to change. This will not occur until water is valued and priced at an appropriate level.

Priority areas for improving water management in the GMS are set out below. Because agriculture dominates water withdrawals, it will be required to play a major role in improving efficiencies. Within the agriculture sector there are a range of approaches that could improve water use efficiencies, reduce risks and protect water quality in both rain-fed and irrigated systems. Maintenance of aquatic ecosystems is essential to food security in the GMS, because of the dependence on fisheries in these ecosystems.

Improvements in Water Management in Rain-fed Systems

Rain-fed agriculture dominates production in the GMS, due to a long rainy season with high rainfall. Most of the wet-season rice crop is either rain-fed or has only limited supplementary irrigation (Mainuddin et al. 2008). Despite a strong focus by regional governments on increasing access to irrigation, significant areas of the plains and uplands may never be irrigable because of topographic, hydrologic or soil constraints: for example, FAO estimates that only 20% of the total potential cropland in Cambodia is irrigable (MAFF and MOWRAM 2007). Thus a large proportion of cropland is likely to remain rain-fed, and it is essential that water management options for rain-fed agriculture are not neglected. Drought is the major risk in the plains and uplands, but rain-fed production in the deltas and floodplains is prone to risks from both floods and droughts: in the major Mekong floods of 2000, over 400,000 ha of rice in Cambodia (MAFF 2009b) and 93,000 ha in Vietnam (Kazama et al. 2002) were estimated to have been destroyed.

Technologies and practices for improving water management at the farm scale are loosely grouped as “agricultural water management” (AWM) technologies. These range from traditional techniques to modern innovations, and include (IWMI 2006) the following:

- In-situ soil and water conservation technologies including conservation agriculture (e.g., planting pits, infiltration ditches, mulching, contour banks).
- Ex-situ rainwater harvesting and water-storage technologies (e.g., small earth dams, tanks, hand-dug shallow wells, runoff harvesting).
- Water-lifting technologies (e.g., treadle pumps, hand pumps) for transferring water to, and/or removing water from, fields.

- Technologies for efficient application of water to plants (e.g., clay pot subsurface irrigation, bucket irrigation, direct application by hose).

Conservation farming approaches can increase production by reducing the risk of intermittent drought stress that is common to rain-fed production systems. Simple approaches to improving the quality of soils through the application of organic matter (waste materials) and/or inorganic natural minerals (clays) will have a positive impact on the water-holding capacity of soils and their nutrient-holding ability. Noble and Suzuki (2005) report typical yield increases of 30-100% in rain-fed lowland, organically grown rice when soils were treated with bentonite clays in field studies in Northeast Thailand to improve nutrient retention and water-holding capacity. Reduced tillage, stubble mulching and other soil conservation practices that reduce evaporation from the soil surface also have a positive impact on the water-storage capacity of soils.

Water harvesting and small-scale water storage for supplementary irrigation in dry spells during flowering or grain-filling can significantly improve yield and reduce risk of crop failure (CA 2007). Small-scale water storage and irrigation systems permit flexibility for farmers to select diverse cropping systems with staggered planting dates that better suit the uncertainties in water availability from season to season, while the water-storage ponds can provide additional income from fish culture (van der Mheen 1999). Small-scale water harvesting using on-farm storage has been successfully implemented in Northeast Thailand as part of the "integrated farming system" promoted by King Bhumipol (Setboonsarng and Gilman 2009) where ideally 30% of farm area is set aside for ponds for water storage used for irrigation and fish culture. In a study in Tamil Nadu, Jayanthi et al. (2000) found that integrated farming requires less water per unit of production than monocropping systems.

IWMI (2006) reviewed a wide range of small-scale AWM technologies available for southern Africa, and concluded that when used appropriately they can provide substantial improvements in household food security and incomes in a cost-effective manner. It was stressed, however, that these approaches are highly specific for particular systems, and must be targeted to suit agroecosystem, soil, microclimate and social contexts. However, water saving techniques are effective only where water availability is a major constraint to production. This may not be the case in many places in the GMS where labor, capital and markets are defining factors.

Breeding drought-tolerant crop varieties that have high water use efficiencies will also contribute to yield increases in water-limiting environments. Trials of drought-tolerant rice varieties in Kampong Cham and Siem Reap in Cambodia increased yields on farmers' fields by 1.0 to 1.6 t/ha (from 1.9 to 3.5 t/ha) compared to currently used varieties (CURE 2009). Similarly, submergence-tolerant varieties currently being introduced in India and the Philippines can significantly reduce crop losses due to flooding (IRRI 2009).

The Cambodian Strategy for Agriculture and Water (2006-2010) concluded that "introduction of improved water management technology for rain-fed agriculture would be more cost-effective, more easily managed, and have more widespread benefits in the long run. It is not a question of one or the other approach, but of choosing where different technologies are appropriate, how their relative monetary and social benefits compare, and how to achieve equitable investments that benefit the whole rural population" (MAFF and MOWRAM 2007).

Improvements in Water Management in Irrigated Systems

Recent FAO studies found that large- to medium-scale public irrigation systems in Asia generally performed well below their potential (Mukherji et al. 2009; Facon 2007). Problems stem mainly from inappropriate design and O&M. Given the high level of existing and planned investment in irrigation infrastructure, improving the performance of these systems must be a high priority. In many older irrigation systems in the GMS, water use is highly inefficient due to poor design of conveyance and application systems combined with a tendency for overirrigation. Increased water use efficiencies can be achieved through upgrading of distribution systems (channel lining, use of pipes) and the adoption of improved technologies, such as drip and pivot irrigation; deficit irrigation, and the production of wet-dry (aerobic) rice.

Intensification of cropping systems through both full and supplementary irrigation in the dry season is needed to realize the full value of irrigation infrastructure. Many systems were initially designed around rice production (for example, low drainage requirements, inflexible scheduling), making it difficult for farmers to diversify into higher-value dry-season crops (Nesbitt 2005). More flexible systems are needed to allow farmers greater control and autonomy of irrigation scheduling, thereby encouraging diversification of farming activities. In South Asia and China, there has been a massive shift to farmer-managed small-scale pumping, even in areas where public irrigation previously dominated – the "atomization" of irrigation (Mukherji et al. 2009). There is evidence of a similar shift in Southeast Asia with a rapid increase in the number of small pumps installed in Vietnam (>800,000 by 1999), Thailand (>3 million by 1999) and more recently in Cambodia (120,000 in 2006) (Mukherji et al. 2009; MAFF 2009b). Small-scale pumping often relies on groundwater sources (see below).

If the risk of flooding of lowland areas increases as a result of climate change, and irrigation is possible, it may be appropriate to shift the main cropping season to the dry season to capitalize on higher yield from higher solar radiation. This trend can already be seen in the Mekong Delta, where the traditional wet-season rice crop accounts for only 10% of the total production, which is now dominated by two irrigated crops in winter-spring and summer-autumn (Government Statistical Office of Vietnam 2009). Such a shift would require major investment in irrigation, but may be an opportunity to implement new and more flexible approaches. In Bangladesh, tracts of flooded ricelands in low-lying areas that are no longer cultivated with deep-water rice, in favor of dry-season irrigated rice, are now under community-based management for floodplain fisheries during the monsoonal season (WorldFish Center 2007).

The inefficiency and low utilization of large- to medium-scale irrigation schemes are frequently attributed to failures in O&M and management (Facon 2007; World Bank 2006; Mukherji et al. 2009). This is due to inadequate funding, training and technical support for agencies managing irrigation schemes, and to institutional failures where central bureaucracies and public-sector irrigation institutions have often lacked the structure and incentives to optimize productivity. It is also due to mistakes in planning and design of the irrigation project that did not take into account the slack time from project completion until farmers could fully change their production systems to adapt to new water conditions that might take many years. The response has been for donors to encourage governments to hand over responsibility for managing irrigation back to farmers through Participatory Irrigation Management/Irrigation Management Transfer (PIM/IMT). However, based on a major review, Mukherji et al. (2009) concluded that "in most of Asia, transferring management from bureaucratic irrigation systems to farmers' groups has neither significantly improved productivity, operation and management, nor has it produced other net benefits…many experts now believe there is a need to look beyond conventional PIM/IMT." Suggested approaches include public-private partnerships for irrigation management, farming out of management services, and unbundling of system management into smaller components.

In all surface irrigated systems there is significant return-flow that needs to be managed in a sustainable manner to prevent long-term negative impacts, as is evident in parts of Northeast Thailand. These return flows often contain high levels of dissolved salts, pesticides and minerals. There are a number of innovative approaches that include sequential (or serial) biological concentration (Paydar et al. 2007) that could effectively utilize this otherwise problematic water thereby increasing water use efficiencies and adding an economic value to wastewater.

With rapid urbanization in GMS countries, the role of urban wastewater within the agriculture sector in the region could hold significant potential in increasing water use efficiencies. This is an area that has not been promoted and one that holds significant implications for closing the nutrient cycle, reducing the costs associated with wastewater treatment plants and increasing water use efficiencies.

Groundwater Development and Conjunctive Use

The development of groundwater resources, either as a sole source or in the context of conjunctive use, may emerge as a key factor in addressing future water issues in the region. Groundwater currently accounts for only a small proportion of irrigation in the GMS, but its use is increasing. In many parts of Asia, there has been a substantial move to use groundwater for irrigation, often even where surface water is available (Mukherji et al. 2009; Shah 2009). This trend is also emerging within the GMS.

Currently, groundwater is used in the GMS primarily to supplement surface water irrigation, often in locations or seasons where water is scarce. As pressures on surface water sources increase due to growing population and climate change, reliance on groundwater is likely to rise. In addition, groundwater can offer an attractive alternative to large, centrally controlled irrigation systems, since it provides smallholder farmers with individual control over their water supply, autonomy in water use and greater flexibility in production systems.

Groundwater plays a major role in the provision of domestic supplies, particularly in smaller settlements, where it is preferred to surface water due to year-round availability and better quality, particularly since it is less prone to microbial contamination. In Cambodia, more than half of the population uses groundwater for domestic needs (MRC 2003), whilst in Lao PDR groundwater is the main source of drinking supplies for the rural population (World Bank 2006).

Technologies are being developed to take advantage of the potential of aquifers to store and transfer water. Managed aquifer recharge, storage, transfer and recovery can be used to enhance water supplies, reduce the need for infrastructure, decrease evaporative losses and improve groundwater quality through dilution. For example, flood water can be pumped to aquifers for later recovery and use; and in highly connected floodplain systems, shallow aquifers can act as delivery systems carrying river water to the floodplain. Managed aquifer recharge (MAR) can also be used to preserve water levels in wetlands that are maintained by groundwater, and to mitigate or control salt-water intrusion into coastal aquifers (NWC 2009). Such technologies could offer significant benefits for dealing with the impacts of climate change in the GMS region. In Thailand, MAR trials are currently underway on ponding-based methods of aquifer recharge in the Phitsanuloke irrigation area (Srisuk et al. forthcoming), riding on the success of similar trials in Vietnam (Nguyen Thi Kim Thoa et al. 2008).

Groundwater resources are thus of emerging but vital importance, but little is known about the size and sustainability of groundwater resources in the GMS. The continued provision of adequate volumes of good quality supplies is under growing threat from falling water tables, contamination, intrusion of salt water and land subsidence. There is a significant risk of unregulated overexploitation of groundwater: over-pumping has already significantly depleted groundwater resources in several areas in Vietnam (MONRE 2009). Unregulated groundwater use may also impact on linked surface water, particularly in the deltas and floodplains where groundwater and surface water are highly connected and must be managed conjunctively to be sustainable.

A comprehensive assessment of groundwater resources, use and potential in the region is urgently needed, as the basis for management plans for the conjunctive use of surface water and groundwater and to assess the potential of new technologies to contribute to water management under climate change.

Protecting Water Quality: Closing the Nutrient Cycle

High-yielding agricultural production systems are dependent on the addition of synthetic fertilizers, in particular industrially produced nitrogen (NH_4 and NO_3) and phosphorus. A significant amount of the applied N and P added to crops is lost from agricultural fields, and ends up in waterways. Excess of nitrogen and phosphorus leads to water-quality problems including eutrophication, harmful algal blooms, hypoxia and declines in wildlife and wildlife habitat, and can impact on human health. As well as the financial cost, nitrate and phosphate fertilizers have high embodied energy; and breakdown of excess nitrogen fertilizers contributes to GHG emissions as nitrous oxide (Galloway et al. 2008).

Reducing the input of industrialized fertilizers is thus an urgent priority. This can be achieved by increasing nutrient use efficiencies: in the USA, nitrogen fertilizer efficiency has increased by 36% since the mid-1970s (Frink et al. 1999). These improvements are a result of significant investments in research and extension education, soil testing and timing of fertilizer applications. Other strategies that could be implemented to increase nutrient efficiencies in cropping systems are the use of crop varieties grown for efficiencies in higher nutrient use; cover crops or reduced tillage to reduce losses associated with leaching, volatilization and erosion; and closing the nitrogen and phosphorus cycles through the application of livestock and human wastes as fertilizers.

Opportunities exist for agricultural reuse of urban wastewater, which provides multiple benefits in terms of enhancing food supply and recycling nutrients although health risks from the use of polluted water must be managed carefully (Raschid-Sally and Jayakody 2008).

Livestock production will become an increasingly important regional component in the agriculture sector as per capita incomes rise. Whilst industrial-scale production of livestock in the region is still in its infancy (e.g., chicken and pork production for global markets) this trend will increase rapidly. The safe handling and sustainable disposal of animal wastes from high-density animal confinement facilities are a challenge but could be viewed as an opportunity. The composting of animal waste to create crop fertilizers and soil amendments offers an opportunity to close the nutrient cycle and improve the quality of soils. The closing of the nutrient cycle will decrease dependence on synthetic fertilizer production.

There are possible advantages of improving efficiencies and minimizing losses through combinations of organic and inorganic fertilizer use. Organic matter effectively acts as a slow-release form of nutrients, but can be fortified with inorganic fertilizers to synchronize releases to meet crop demand. The advantage of such an approach would be a dramatic decrease in the need for inorganic nutrients that would have significant positive implications with respect to energy saving in the manufacture of inorganic fertilizers. Research is needed to develop innovative fertilizer delivery platforms that supply nutrients in a far more efficient and sustainable manner.

Nutrient management may take on new urgency as global supplies of phosphorus are depleted. Most of the world's farms do not have or do not receive adequate amounts of phosphate and demand for P fertilizer is increasing. Projections of the life span of the remaining P reserves range from 60 to 130 years (Dery and Anderson 2007); in 2007-2008, the price of phosphate rose by 250% (Jung 2008). The key response to “peak phosphorus” is to re-create a cycle of nutrients by returning animal and human wastes to the soil.

Management of Aquatic Ecosystems and Environmental Flows

The significance of freshwater fisheries to both food security and the economies of the GMS countries means that maintaining the health of freshwater ecosystems is a very important priority. Aquatic ecosystems also provide a wide range of ecosystem services beyond fish production: wetlands and lakes provide flood attenuation, groundwater recharge and water purification

(Foley et al. 2005; CA 2007). Wetlands are important agricultural systems: both deepwater and recession rice capitalize on natural wetland habitats, and paddy fields essentially mimic the water retention of natural wetlands (McCartney et al. forthcoming).

Aquatic ecosystem health and associated environmental services deteriorate when natural flows of water, sediments and organic materials are substantially disrupted or modified, for example, by damming or diversion of rivers, or alienation of floodplains by construction of infrastructure. Hydropower development, diversion of water for agriculture and urbanization and road construction all place increasing pressure on the aquatic ecosystems of the GMS. Proposed hydropower development in the major river basins of the GMS (described above) will result in changes to river flows at an unprecedented scale and rate, bringing larger changes than those predicted from climate change and in a much shorter time frame (TKK and SEA START RC 2009).

Definition of the magnitude and timing of flows needed to maintain rivers, lakes and wetlands in an ecologically acceptable condition (environmental flows or environmental water demand) has been the subject of extensive debate and study internationally (Arthington et al. 2006; Richter et al. 2006). A preliminary assessment of the environmental impacts of flow modification has been conducted for the Mekong (MRCS/IBFM 2006), but few studies have been carried out elsewhere in the GMS. However, methods have been developed for assessing and managing environmental flows where detailed hydroecological data are not available (Smakhtin et al. 2007; Smakhtin and Eriyagama 2008; Abbasov and Smakhtin 2009; Poff et al. 2009) and can provide the basis for adaptive management programs until more comprehensive studies are available. There is an urgent need to incorporate these approaches into water resources planning before extensive developments are undertaken, to prevent degradation of fisheries and other environmental services observed in other parts of the world (World Commission on Dams 2000b). A major constraint in the adoption of these approaches is seeking agreement between the range of stakeholders and managers from different sectors and locations, in particular for the transboundary international rivers as in the GMS.

Maintenance of flows, though essential, is not the only factor in maintaining the health of aquatic ecosystems. Aspects such as maintaining wetland vegetation, connectivity of wetland habitats, migration paths and water quality must also be taken into account. For example, in the Tonle Sap system, clearance of flooded forests, alienation of the floodplain by construction of roads and levees, and changes in the flux of sediment and nutrient into the lake all pose threats to the viability of the lake's ecosystems (Baran et al. 2007; Kummu and Varis 2007; Krittasudthacheewa and Apirumanekul 2008). In river systems, migration paths and refuge habitats such as deep pools must also be maintained (Poulsen et al. 2002). Thus environmental flow studies must be carried out in conjunction with a landscape-scale assessment of the functioning of aquatic ecosystems.

The discourse around environmental flows relies heavily on the concept that thresholds of "acceptable" impacts can be defined and that trade-offs can be made balancing allocation of water in different sectors. Friend and Blake (2009) argue there is increasing evidence that the scale of impacts of dam construction on aquatic ecosystems is so great that it does not allow for trade-offs. McCartney (2009) cautions that although a wide range of measures has been developed to ameliorate the negative impacts of dams, many interventions fail, either for technical reasons or as a consequence of a variety of socioeconomic constraints, and that lack of hydroecological understanding remains a key constraint to successful environmental protection.

In the low GDP countries of the GMS – as in much of the developing world – water infrastructural projects are an important component of national development plans. In this context, it is difficult for decision makers to prioritize reserving flow for the environment over the more urgent requirements of income generation and poverty reduction. Environmental flows were expected to help minimize conflicts among water-use sectors but, in practice, they have caused confusion because of the difficulty in quantifying the needs and impacts of different uses. Thus in the developing world, environmental flows have often been dismissed as irrelevant, encapsulating an antidevelopment stance, largely about conservation of ecosystems and biodiversity for their own sake.

However, there is increasing recognition of not only the much broader economic and social importance of environmental flows but their role in both alleviating current poverty and maintaining options for the future (SWH 2009). In the GMS, subsistence livelihoods are inextricably linked with ecosystem health, and maintenance of aquatic ecosystems is an essential component of food security for the poor (see section on Water, fisheries and aquatic ecosystems, p. 11). Equally importantly, environmental flows can be seen as preserving options for future use: if people use the flow for certain production benefits now (e.g., hydropower), they may lose other current and future benefits (such as fisheries), incur future costs (such as loss of fertile sediment trapped in the reservoir) or restrict alternative development options (such as ecotourism). These dimensions of environmental flows have been explicitly recognized in the methodology of Downstream Response to Imposed Flow Transition (DRIFT) which focuses on both environmental and sociological benefits of flows, including subsistence uses (King et al. 2003). To gain more policy traction in a development context, the definition of environmental flows needs to be broadened to explicitly include subsistence uses and the concept of “flows for the future.”

Climate Change Planning in the GMS

Over the last few years, considerable effort has gone into initiating response strategies for climate change in the GMS. All countries in the region are preparing National Adaptation Action Plans (NAPAs), many studies have examined options for adaptation, and a wide range of potential technical and social responses have been identified (see, e.g., Resurreccion et al. 2008; MRC 2009b). As part of adaptation planning, options for mitigating GHG emissions from GMS countries have also been considered. Agriculture is the major contributor of GHG emissions from all GMS countries, and could thus play a correspondingly large part in mitigation efforts (Smith et al. 2007; World Bank 2008; ADB 2009a).

In formulating adaptation priorities and strategies in the water sector, two important points must be taken into consideration: the high degree of uncertainty surrounding the pace and direction of changes in water availability and the rapid rate of change due to other, non-climate factors. There are no defined boundaries between climate-specific and non-climate-specific adaptations (Resurreccion et al. 2008). Response strategies must be formulated in the context of the whole range of impacts and drivers. Responses range from planned (such as macroeconomic policies) to autonomous (such as decisions by individual producers to change crops in the face of fluctuating prices and demand).

McGray et al. (2007) point out that adaptation and development are intimately interlinked, and that it is not always possible or productive to draw a distinction between the two. They define a continuum of responses between development activities (aimed at reducing vulnerability through building capacities that can help address a range of challenges, including the effects of climate change) and explicit adaptation measures (addressing specific impacts of climate change); see Box 2. In a context where there is uncertainty around climate projections, there is a high risk in implementing

Box 2. Framing adaptation: a continuum of approaches

The range of adaptation activities may be framed as a continuum of responses to climate change, roughly divided into four types of adaptation efforts:

1. Addressing the Drivers of Vulnerability

At the development end of the spectrum are activities that not only reduce poverty and address other fundamental shortages of capability but make people vulnerable to harm. Very little attention to specific climate-change impacts is paid during these interventions although they help buffer households and communities against climate trends or shocks. Sample activities include efforts to improve livelihoods, literacy, and women's rights, and even projects that address HIV/AIDS.

2. Building Response Capacity

Adaptation activities focus on building robust systems for problem-solving. These capacity-building efforts lay the foundation for more targeted actions, and substantially overlap many institution-building and technological approaches familiar to the development community. Examples include the development of robust communications and planning processes, and the improvement of mapping, weather monitoring, and management practices of natural resources.

3. Managing Climate Risk

Climate information is incorporated into decisions to reduce negative effects on resources and livelihoods, accommodating the fact that often the effects of climate change are not easily distinguished from those of hazards within the historic range of climate variability. Examples include disaster-response planning activities, drought-resistant crops, and efforts to "climate-proof" physical infrastructure.

4. Confronting Climate Change

Actions focus almost exclusively on addressing impacts associated with climate change, typically targeting climate risks that are clearly outside historic climate variability, and with little bearing on risks that stem from anything other than anthropogenic climate change. Examples include communities that relocate in response to sea-level rise and responses to glacial melting.

(*Source*: McGray et al. 2007)

explicit adaptation measures since these may turn out to be maladaptive. This underscores the importance of planning in terms of recognizing and maintaining the distinction between climate change and climate variability; if short-term variability is mistaken for trend, and adaptation responses are planned on that basis, serious errors could occur.

In contrast, response strategies that have, at their core, measures to reduce vulnerability, build resilience of production systems and improve adaptive capacity of rural communities constitute "no-regrets" options. A robust approach is needed, seeking solutions that address current problems and build resilience, regardless of the direction of change (World Bank 2009c; Danish Ministry of Foreign Affairs and Partners 2009). In the context of water management, options such as those described above which increase water productivity and decrease water-related risks will generally constitute "no-regrets" options, in that they also provide benefits in terms of production or environmental outcomes. Similarly, producers in the region have always lived with climate variability and have many coping strategies for droughts and floods that will form the basis for adapting to climate change (Friend et al. 2006), and many of these are "no-regrets" responses. Incorporating the concept of climate risk into planning and investment decisions is an important strategy for managing current as well as future climate variability.

Appropriate responses will be highly context-specific, depending on physical and social conditions as well as interactions with measures that might be recommended in other sectors. Trade-offs between sectors, or between short- and long-term outcomes, may be required. Changing conditions may mean that previously viable strategies become infeasible or maladaptive, for example, expenditure on water storage may be lost if upstream changes in either climate or infrastructure result in changes in water availability. Adaptive management strategies will be required to deal with uncertainty and change.

All countries have recognized the importance of building adaptive capacity in communities so that they are better able to deal with unforeseen changes. Social adaptation will be as important as technical measures in ensuring the long-term viability of rural communities and agricultural production. It is widely recognized that capacity to adapt to change is closely linked to socioeconomic factors such as poverty, diversification of income sources, level of education, and access to infrastructure and technology (Anshory-Yusuf and Francisco 2009; IPCC 2007). Promoting broadly based agricultural development to lift rural communities out of poverty is probably the most effective adaption strategy available.

Adaptation Priorities

In the same way as water management strategies, effective adaptation responses must be tailored to fit specific physical, social and economic conditions. Priorities in different physiographic zones will be very different, and an analysis of options for responding to climate change in the different physiographic zones is set out in Table 5. However, even within similar physical environments, the social and economic context will determine the relevance of particular approaches.

In the *deltas* the threat of sea-level rise will dominate longer-term planning, with difficult decisions to be made now regarding protecting or abandoning low-lying productive land and infrastructure under impacts of this slow process. Flood protection and disaster preparedness programs have high priority in these zones under all the NAPAs, to protect vulnerable coastal populations. Major investments in infrastructure to protect crops from floods and salinity intrusion (dykes, pumps) are already planned and/or underway in some areas, for example, in the Mekong Delta (Tuan et al. 2007).

Because they are the end points of the river systems, water impacts from the upstream will be passed on to the deltas, and basin-scale planning and water allocation agreements are needed to reduce vulnerability of deltas to upstream use and optimize multiuse water systems, including hydropower. Pressure on dry-season water availability could be reduced by shifting crop calendars to balance full dry-season irrigation with supplementary irrigation of early or late wet-season crops, as well as by improvements in irrigation efficiency. Reuse of wastewater from major cities for peri-urban agriculture offers benefits in nutrient recycling as well as in reduced water use. Conjunctive use of groundwater and surface water may reduce the pressure on surface water resources, but in most cases, little is known about the extent of groundwater resources and the sustainable limits for their use. Overpumping from groundwater has already resulted in declining water tables and saline intrusion into aquifers in the Mekong (MONRE 2009) and subsidence in urban areas of Bangkok (Phien-wej et al. 2006).

Improvements in brackish water aquaculture, integrated mangrove/shrimp cultivation, expansion of freshwater aquaculture and integration into rice production systems will be important components of maintaining and increasing productivity in the deltas. Changes in rice cultivation methods to reduce methane emissions (wet-dry cultivation; Allen et al. 1996) may involve trade-offs against aquaculture potential in flooded systems. Aquaculture of mollusks and seaweed can provide carbon sequestration as well as high productivity (de Silva and Soto 2008).

TABLE 5. Potential responses to climate change by the agroecological zone in the GMS.

Objectives	Deltas and Tonle Sap	Lowland plains and plateaus	Intensively used uplands	Forested uplands	Coastal areas
Water management	• Basin-scale planning and water allocation agreements to reduce vulnerability of deltas due to upstream use and optimize multiuse water systems, including hydropower. • Integrate actions on infrastructure for long-term flood control and protection from sea-level rise into current planning. • Improve irrigation efficiency. • Balancing supplementary irrigation vs. full dry-season irrigation. • Reuse of wastewater from major cities for peri-urban agriculture. • Conjunctive use of groundwater/surface water in critical periods.	• Land-suitability assessment of lowland zones to identify areas of high potential for conversion to permanent agriculture and expansion of irrigation. • Range of water storage and management options, such as rainfall conservation practices, small-scale water storage, conservation farming, improved supplementary irrigation, improved soil management, especially in plantations, to reduce water use and prevent soil degradation, and investigation of groundwater potential.	Same responses as in the lowland plains and plateaus.	Same responses as in the intensively used uplands.	Same responses as in the deltas, but more vulnerable to sea-level rise, particularly in Myanmar and Vietnam where production is more dispersed and protection works such as dikes and seawalls are less likely to be economically viable so that regeneration of mangroves is the most suitable alternative. Implement integrated coastal zone management.
Crop and livestock management	• Continuing/enhancing the role as major food-production areas by increasing overall production. • Diversification with cropping systems that optimize water use. • Improved crop varieties (drought, flood and pest resistance). • Retention of traditional cultivation methods which use flood pulse/rainfall. • Changes in rice cultivation to reduce water use (e.g., direct seeding, wet-dry alternative irrigation). • Increasing yield by integrated nutrient management and improved cultivation practices. • Intensification to double cropping where water is not yet limiting factors (Tonle Sap and Irrawaddy). • Intensive forage-based livestock production with improved pastures. • Development policy strategies to assist and protect small-scale farmers from livelihood	• Applying cropping systems, including agroforestry/perennial crops that optimize water use. • Retention of traditional cultivation methods which use flood pulse/rainfall. • Balancing supplementary irrigation vs, full dry-season irrigation. • Changes in rice cultivation to reduce water use – direct seeding, wet-dry cultivation. • Amelioration of soil degradation through the use of conservation farming practices to reduce soil erosion and increase soil fertility. • Diversified sustainable smallholder agricultural systems incorporating cropping, livestock and aquaculture to reduce risk for small-scale producers. • Optimizing opportunities for agriculture from hydropower development.	Same responses as in the lowland plains and plateaus, with additional responses for sloping features: • Conservation farming approaches to protect and enhance productive capacity. • Reduced tillage and direct seeding, mulch-based conservation (DMC) farming. • Improved fallow systems. • Cultivation of understory with tree crops in the plantations. • Improved livestock management systems: forage crops, improved pastures, semi-intensive cultivation to reduce grazing pressure on steep lands – potential mitigation benefits through decreased methane emissions.	Same responses as in the intensively used uplands.	Same responses as in the deltas for the small coastal deltas, and as in the intensively used uplands for the upland coastal areas, with highest priority for maintenance/enhancement of food production capacity in the face of large and growing populations and possible loss of productive land, in particular, in Myanmar and Vietnam. Implement integrated management of coastal zones.

(Continued)

TABLE 5. Potential responses to climate change by the agroecological zone in the GMS (continued).

Objectives	Deltas and Tonle Sap	Lowland plains and plateaus	Intensively used uplands	Forested uplands	Coastal areas
	and financial losses due to increasingly severe weather hazards.		• Reforestation of steep lands–“win-win” erosion reduction and mitigation benefits.		
Fisheries/ aquacultural management	• Diversify targeted species, adjust fishing effort/strategies, implement management of community-based fisheries. • Invest in improved vessel design (for better stability, safety and sea-to-shore communication). • Exit the fishery and diversify livelihood systems. • Introduce aquaculture to salinized and flooded areas. • Replace the use of trash fish with formulated feeds. • Diversify culture species, especially those lower in the food chain such as seaweed, high-value invertebrates (mollusks, sea cucumber, sea urchins, abalones and giant clams). • Develop salinity-tolerant strains of freshwater species, move culture further upstream, select faster-growing species or strains. • Improve aquaculture, e.g., proper infrastructural design and water management, enhance aquacultural skills and provide infrastructure. • Promote ecologically friendly integration of aquaculture with other food-production activities, e.g., rice-fish systems, mangrove-crab and mangrove-shrimp systems. • Hatchery technology to replace wild seed stock. • Increase monitoring of harmful algal blooms.	• Assessment of climate change impacts on hydropower development and, subsequently, on capture fisheries to find out suitable alternatives for mitigation. • Developing reservoir fisheries and expansion of aquaculture in reservoirs/lakes. • Investigation of potential synergies or opportunities for aquaculture, in particular, in rice-fish systems. • Banning stocking of certain exotic fish species in the natural water bodies (in Lao PDR), but need to be accompanied by enhancing growth of natural populations.	Same responses as in the lowland plains and plateaus.	Same responses as in the intensively used uplands.	Same responses as in the deltas for the small coastal deltas, and as in the intensively used uplands for the upland coastal areas, with highest priority for maintenance/ enhancement of food production capacity in the face of large and growing populations and possible loss of productive land, in particular, in Myanmar and Vietnam. Implement integrated management of coastal zones.

(Continued)

TABLE 5. Potential responses to climate change by the agroecological zone in the GMS (continued).

Objectives	Deltas and Tonle Sap	Lowland plains and plateaus	Intensively used uplands	Forested uplands	Coastal areas
Land cover management	• Strengthen or build physical defenses. • Rehabilitate vegetation buffer (regrowth of degraded forests), e.g., 100,000 ha of melaleuca in Mekong.	• Restoration of degraded forests for mitigation benefits. • Apply suitable agroforestry/ perennial crops.	Same responses as in the lowland plains and plateaus.	Same responses as in the intensively used uplands.	Same responses as in the deltas for the small coastal deltas, and as in the intensively used uplands for the upland coastal areas.
Safeguarding communities	• Introduce insurance schemes. • Implement disaster preparedness programs (e.g., teach survival skills to vulnerable groups; have early warning systems; have in place gender-sensitive post-disaster response plans). • Enhance capacity for livelihood transition and diversify economic activities. • Implement managed retreat – move settlements inland.	• Introduce insurance schemes. • Implement disaster-preparedness programs (e.g., teach survival skills to vulnerable groups; have early warning systems; have in place gender-sensitive post-disaster response plans). • Enhance capacity for livelihood transition and diversify economic activities.	Same responses as in the lowland plains and plateaus.	Same responses as in the intensively used uplands.	Same responses as in the deltas.

In the *plains* and *plateaus*, responses to climate change will be mainly about management of scarce water. A range of crop management techniques are available to reduce water use, for example, retention of traditional cultivation methods which use the flood pulse and rainfall, and changes in rice cultivation such as direct seeding and wet-dry cultivation methods. Rainfall conservation practices in rain-fed areas (small-scale water storage, conservation farming) can improve crop yields and reduce production risks. Supplementary irrigation and use of crops such as groundnut and soybean with low water demand can reduce irrigation demands, assuming the market limitations of these crops can be solved. Low levels of utilization of irrigation over much of the plains suggest potential to increase production by expanding and improving irrigation, but Molle and Floch (2008) caution that ambitious projects for irrigation expansion (such as "Greening Isan" and Thai Water Grid) have not come to fruition for a range of social and economic reasons. Wet-dry rice cultivation to reduce methane may be more feasible here than in the deltas, with co-benefits through decreased water use. However, labor and capital are major constraints for application of new cultivation techniques. Large-scale agroforestry plantations and cultivation of biofuels could provide significant carbon sequestration, but these options need to be assessed carefully since there are significant risks of competition with food crops (both land and water); and social disruption accompanying large-scale plantations. Assessment of land suitability of lowland zones is urgently needed to identify areas of high potential for conversion to permanent agriculture (and conversely, to identify areas not suitable for conversion), taking into account possible changes in crop suitability over time. Coordinated planning is important in order to optimize opportunities for irrigation and reservoir fisheries in conjunction with hydropower development.

In the *uplands*, there is a range of "win-win" solutions which offer increased production, improvements in water management and reductions in GHG emissions. Conservation farming techniques (reduced tillage, improved fallow, mulching) sequester carbon, improve water productivity and reduce soil erosion as well as increase production (Valentin et al. 2008; Fowler and Rockström 2001; Hobbs 2007). Improved livestock management systems (forage crops, improved pastures, semi-intensive cultivation) reduce grazing pressure on steep lands all of which have potential mitigation benefits through decreased methane emissions (Steinfeld et al. 2006). Reversion of steep lands to forests (already observed in parts of Vietnam, Yunnan and Thailand; UNEP and TEI 2007) reduces soil erosion and increases carbon sequestration. Protection and reestablishment of forests also protect water-regulating functions of catchments and potentially result in significant GHG sequestration (Angelsen 2008). However, in reality this alternative is only possible in areas where economic development has reached a level where conversion of forest to agriculture is less profitable than other, nonfarm activities.

In the *coastal zones*, significant areas of the coastal plains are vulnerable to sea-level rise, particularly in Vietnam and the Rakhine Delta in Myanmar (Dasgupta et al. 2007). Production in these areas is more dispersed than in the deltas, and protection works are less likely to be economically viable. The coastal fishing populations are most vulnerable to inclement coastal- and sea-weather conditions, and being located right at the water's edge, fishing and fish farming equipment and structures bear the brunt of storms. High dependence on marine and wetland resources means that these areas are vulnerable to ecological changes due to sea-level rise or increase in the temperature of the surface of the sea, and diversification of livelihoods will be an important priority. Reduction of disaster risks and preparedness for storms, floods, and post-disaster interventions can reduce vulnerability to climate-related disasters. There is some potential for mitigation of GHG emissions through agroforestry, and improved livestock management.

Water Dimensions of Mitigation

Two aspects of climate change mitigation efforts are likely to have important ramifications for water management: attempts to reduce GHG emissions from agriculture and land use change; and increased production of biofuels.

Land use change

The forestry and agriculture sectors contribute 80% of total emissions from Lao PDR and Cambodia, and 60% from Vietnam (Morton 2008; ADB 2009a). Emissions result mainly from the release of CO_2 due to land use change, deforestation and forest degradation; release of CO_2 and N_2O from soils; and methane emissions from rice paddies and livestock (Smith et al. 2007; Galloway et al. 2004).

Smith et al. (2007) estimated that Southeast Asia has the greatest technical potential for mitigation of any region globally, through a combination of direct reduction of emissions (by reduction of forest clearing and conversion), enhancing GHG removal (by increasing carbon sinks in both vegetation cover and soil carbon) and displacing emission (e.g., by the use of biofuels). Mitigation opportunities from agriculture include the following:

- *Increasing soil carbon storage* by improved agronomic practices such as minimum tillage, residue return, use of cover crops, legume rotations (though there may be offsets between C storage and release of N_2O, depending on the nutrient status of soils).
- *Reversion of cropland* to pasture or tree cover, over the entire land area, or in localized spots, such as grassed waterways, field margins, or shelter belts.
- *Reforestation* and improvement of forest quality addressed under the UNFCCC through the Reducing Emissions from Deforestation and Forest Degradation (REDD) program, and a system of financial incentives and payments for reducing carbon emissions associated with deforestation (Angelsen 2008; Vickers 2009).
- *Nutrient management* and use of urban wastewater and livestock wastes as fertilizers to reduce N_2O emissions.
- *Reduction of methane emissions from rice* by wet-dry cultivation (Allen et al. 1996) and by minimizing incorporation of crop residues prior to planting (Sass et al. 1991). There is also evidence that methane emissions decrease as yields increase (Denier van der Gon et al. 2002).
- *Reduction of methane emissions from livestock* through the use of improved forages, improved pastures and breeding of animals with a higher efficiency of feed conversion (Steinfeld et al. 2006).
- *Culture of aquatic organisms lower down the food chain*, such as mollusk and seaweed, can contribute to carbon sequestration. Seaweed culture far exceeds the potential carbon sequestration that could be obtained through other agricultural activities for a comparable area (de Silva and Soto 2008).

All these practices have implications for water use. In some cases, there may be synergistic benefits: for example, minimum tillage can improve retention as well as carbon storage. In other cases, trade-offs will be required and a careful analysis must be made of overall benefits: for example, large-scale reforestation to increase carbon sequestration may decrease water yield for protracted periods.

Internationally, there is increasing recognition of the potential role of agriculture and land management in mitigation efforts, and this calls for inclusion of mitigation from land use changes as measures eligible for payment for carbon credits (Danish Ministry of Foreign Affairs and Partners 2009). If successful, this could result in major shifts in land use in some areas, including parts of the GMS (particularly in the uplands, where reforestation may become economically viable). It is important that the implications for water management of large-scale land use changes are taken into account in planning and implementing mitigation initiatives under schemes such as REDD (Angelsen 2008).

Biofuels

Concerns about CO_2 emissions from fossil fuels and rising oil prices have driven international interest to biofuels, solid fuels such as wood and charcoal, used mainly for cooking and heating, and liquid fuels such as ethanol and biodiesel, produced from crops as a replacement for fossil fuels in transport (Howarth et al. 2009). Both have implications for water management, in different ways.

The GMS region has traditionally relied very heavily on solid biofuels as an energy source, for example, Messerli et al. (2008) report that 95% of Lao PDR households use wood or charcoal as the main energy source for cooking and, similarly, UNDP (2008) reports that almost all rural households in Cambodia rely on fuelwood or charcoal for cooking. Demand for fuelwood has been a significant driver of deforestation in the GMS (UNEP and TEI 2007), and governments and conservation agencies in the region have promoted shifts to alternative fuels (biogas, kerosene, electricity) as an important component of strategies to combat loss of forests and resulting watershed degradation. However, proposed changes to the Kyoto Protocol to broaden the application of carbon credits for afforestation and reforestation could mean that managed agroforestry for fuelwood (combined with more efficient stoves and improved technologies for charcoal production; GERES 2009) will become an economically viable option. Changes in the carbon markets could drive significant increases in reforestation, with concomitant impacts on the quality and availability of water.

Demand for liquid biofuels in the GMS is increasing rapidly. China expects biofuels to supply 15% of its transportation energy needs by 2020 (USDA FAS 2006). The Government of Vietnam is committed to developing biofuels for the transport sector, aiming to reach 5 billion liters per year of bioethanol and 500 million liters per year of biodiesel (Morton 2008). The Government of Thailand is strongly promoting the production and use of biofuels through tax incentives, mandatory biodiesel production, and low interest loans to palm-oil producers. As a result, demand for palm-oil is predicted to grow from 31 million liters in 2006 to 492 million liters per year by 2010, requiring an additional 400,000 of palm-oil plantings (USDA FAS 2007). Neither Lao PDR nor Cambodia has set targets for biofuel production, but many of the large plantation concessions granted in the last 5 years have been for crops suitable for biofuels (oil palm, sorghum, *jatropha*; Voladet 2008; MAFF 2009b). When global fuel price increased during the last few years the Government of Lao PDR approved plans to plant 100,000 ha of jatropha to ensure supplies for a *biodiesel* plant (Theuambounmy 2007).

Several studies have pointed out the potential risks of biofuel production competing with food crops for land and water (e.g., de Fraiture et al. 2008; Howarth et al. 2009). Pursuing biofuel production in water-scarce areas will put pressure on an already stressed resource, especially if it is using a crop that requires irrigation (such as sugarcane). However, de Fraiture et al. (2008) point out that crops such as sweet sorghum, which use much less water, may be a viable option in rain-fed areas and on marginal lands; and tree crops such as jatropha could be incorporated into agroforestry systems.

The economic viability of biofuels will depend on market forces, including fuel and food prices, and may be heavily influenced by global policies affecting carbon markets. Subsidies for biofuels or establishment of carbon credits for biofuels (e.g., under the UNFCCC Clean Development Mechanism) could drive significant land use change, and the impacts of such policies on land use, water availability and food production must be carefully assessed.

Conclusions

Models of climate change in the GMS to 2050 consistently indicate a rise in temperature across the region, but there is no clear regional trend in projections for rainfall. The degree of uncertainty associated with projections is high, and becomes even greater when changes in rainfall are translated into changes in runoff, river flow and water availability. There is some consensus that an increase in the incidence of both floods and droughts may occur, but the magnitude, timing or spatial distribution of such changes are not clear. Water availability in the GMS is already quite variable – the annual pulse of the monsoon is regular, but has a high degree of interannual variability so that floods and droughts are both common. Despite reports of observed changes in climate patterns in the region, statistical analysis of climate records provides no compelling evidence that observed patterns over the last 10 years are outside the bounds of historical variability.

In the short to the medium term (10 to 40 years), the incremental impacts of climate change are likely to be within the range of natural variability and will be masked by it. In contrast, social and economic drivers are already forcing visible regional change at a rapid pace. Changes in agricultural production and development of hydropower are modifying both demand for, and availability of, water resources, and these trends are predicted to accelerate. Climate is only one driver of change, and adaptation to climate change will take place in a highly dynamic and uncertain context, with systems responding to a wide range of pressures and no defined boundaries between climate-specific and non-climate-specific adaptations.

Given the high degree of uncertainty associated with climate projections and the prospect that stationarity may no longer apply in hydrological assessments (Milly et al. 2008), it is counterproductive to rely too heavily on current modeled projections as the basis for adaptation planning to address specific impacts. A more robust approach is needed, seeking solutions that address current problems and vulnerabilities, and build resilience, regardless of the direction of change. One of the major factors determining resilience is economic status – poverty reduction is critical to underpin adaptation efforts in all sectors.

Meeting the region’s food requirements over the coming decades will require large increases in agricultural water or significant increases in water productivity in both irrigated and rain-fed production systems. All countries have policies promoting commercial, export-oriented agricultural development which will place even greater demands on water resources. There is a range of technically feasible “no-regrets” options to increase water use productivity and reduce water-related risks. Rain-fed agriculture is likely to continue as the dominant production mode in the GMS for the foreseeable future, and small-scale, on-farm water management approaches should be an important priority. Since changes in land and water use practice are sought from poor farmers whose livelihood options are limited, new mechanisms for promoting sustainable water use are needed, drawing on the experience from emerging financial models such as payment for environmental services, mitigation payments through schemes such as REDD and harnessing global trade to promote change.

Groundwater is likely to supply at least some of the additional water demand, but information on the extent and sustainability of groundwater resources in the region is limited. A comprehensive assessment of groundwater resources (including surface water and groundwater connectivity) is needed as the basis for coordinated water resources planning. Beneficial outcomes from the conjunctive use of surface water and groundwater are dependent upon evolving institutional and management arrangements. Typically, the management of both surface water and groundwater is fragmented and both resources are planned and managed quite separately.

Proposed hydropower development in the major river basins of the GMS will result in changes to river flows at an unprecedented scale and rate, bringing larger changes than those predicted from climate change and in a much shorter time frame. The importance of freshwater fisheries to food security in the region underscores the importance of protecting the productive capacity of freshwater ecosystems from the impacts of these changes. This requires attention not only to environmental flows but also to habitat coherence and connectivity at the landscape scale. Preliminary assessments of environmental-flow requirements of all major rivers in the basin should be an urgent priority, with a coordinated research effort on hydroecological processes and relationships across the GMS in the longer term.

A high proportion of the research effort in the region has focused on the Mekong, the largest of the region's river basins. Hydrological and ecological information for the region's other major river basins is limited, and this lack will severely constrain planning and monitoring of water resources. Compilation of consistent hydrological data and models across the whole GMS is an important research priority.

Much of the development of agriculture, mining and hydropower that will define water resource use in the GMS over the next 10 to 20 years is driven by private, often external, investors. A coordinated approach to planning is generally lacking, even within countries. While the benefits and impacts of individual projects may be assessed, there is rarely adequate analysis of the cumulative benefits and impacts of multiple projects at the basin, catchment or national scale. Strategic environmental assessments help find a balance between economic development, social equity and environmental sustainability in planning infrastructural development, but such approaches will only be successful if ways can be found to involve private-sector investors in planning at the early stages.

Projections indicate that the impacts of climate change on water resources in the GMS over the next 20-30 years are likely to be small compared to those of economic, demographic and environmental changes. This “breathing space” provides an opportunity for countries and communities to reshape their water management systems, to enable them to deal with the more extreme changes expected after 2050. The most effective strategies for adaptation will be those that promote more productive water use, reduce water-related risk and vulnerability, and build the overall resilience of rural communities.

References

Abbasov, R. K.; Smakhtin, V. U. 2009. Introducing environmental thresholds into water withdrawal management of mountain streams in the Kura River basin, Azerbaijan. *Hydrological Sciences Journal* 54(6):1068-1078.

ADB (Asian Development Bank). 2004. Cumulative impact analysis and Nam Theun 2 contributions: Final report. Prepared by NORPLAN and EcoLao for Asian Development Bank, 143p.

ADB. 2008. *Key indicators for Asia and the Pacific. 2008*. 39th edition. Manila, Philippines: ADB.

ADB. 2009a. *The economics of climate change in Southeast Asia: A regional review*. Manila, Philippines: ADB.

ADB. 2009b. *Key indicators for Asia and the Pacific. 2009*. 40th edition. Manila, Philippines: ADB.

ADB. 2009c. *GMS hydropower dams*. Manila, Philippines: ADB. *http://www.gms-eoc.org/MapTools/GoogleEarth.aspx* (accessed March 2009).

ADB-GMS (Greater Mekong Subregion). 2010. *http://www.adb.org/GMS/*

Allen, L.H.; Baker, J.T.; Boote, K.J. 1996. The CO_2 fertilization effect: Higher carbohydrate production and retention as biomass and seed yield. In: *Global climate change and agricultural production. Direct and indirect effects of changing hydrological, pedological and plant physiological processes*, ed. Bazzaz, F.; Sombroek, W. Rome: FAO; New York: John Wiley and Sons.

Angelsen, A. 2008. *Moving ahead with REDD: Issues, options and implications*. Bogor, Indonesia: Center for International Forestry Research (CIFOR).

Anshory-Yusuf, A.; Francisco, H. 2009. *Climate change vulnerability mapping for Southeast Asia*. Economy and Environment Program for Southeast Asia (EEPSEA). Singapore: EEPSEA, 32p.

Arthington, A.H.; Bunn, S.E.; Poff, N.L.; Naiman, R.J. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* 16(4): 1311-1318.

Associated Press. 2009. *http://sg.news.yahoo.com/ap/20090319/tbs-as-myanmar-foreign-investment-e285837.html* (accessed April 2009).

Baran, E. 2005. *Cambodian inland fisheries: Facts, figures and context*. Penang, Malaysia: WorldFish Center.

Baran, E. 2006. *Fish migration triggers in the Lower Mekong basin and other tropical freshwater systems*. MRC Technical Paper No. 14. Vientiane: Mekong River Commission, 56p.

Baran, E.; Starr, P.; Kura, Y. 2007. *Influence of built structures on Tonle Sap fisheries. Synthesis report*. Phnom Penh: Cambodian National Mekong Committee and the WorldFish Center.

Bates, B.C.; Kundzewicz, Z.W.; Wu, S.; Palutikof, J.P., eds. 2008. *Climate change and water*. IPCC Technical Paper VI. Geneva: IPCC Secretariat, 210p.

CA (Comprehensive Assessment of Water Management in Agriculture). 2007. *Water for food, water for life: A comprehensive assessment of water management in agriculture*. London: Earthscan; Colombo: International Water Management Institute.

Chaudhry, P.; Ruysschaert, G. 2007. *Climate change and human development in Vietnam*. UNDP Human Development Report Occasional Paper 2007/46 1-18.

CIAP (Cambodia-IRRI-Australia Project). 1999. *Cambodia-IRRI-Australia Project annual research report*. Phnom Penh, Cambodia: CIAP, 178p.

Coates, D. 2002. *Inland capture fisheries statistics of Southeast Asia: Current status and information needs*. Asia-Pacific Fishery Commission, Bangkok. Thailand RAP publication No. 2002/1. Bangkok, Thailand: FAO, 114p.

Cruz, R.V.; Harasawa, H.; Lal, M.; Wu, S.; Anokhin, Y.; Punsalmaa, B.; Honda, Y.; Jafari, M.; Li, C.; Huu Ninh, N. 2007. Asia. In: *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* ed. Parry, M.L.; Canziani, O.F.; Palutikof, J.P.; van der Linden, P.J.; Hanson, C.E., 469-506. Cambridge, UK: Cambridge University Press.

CURE (Consortium for Unfavorable Rice Environments). 2009. Activities of CURE in Cambodia. Unpublished report compiled for USAID.

Danh, V.T. 2008. *Household switching behavior in the use of groundwater in the Mekong delta, Vietnam*. EEPSEA and International Development Research Centre Report. Singapore: EEPSEA.

Danish Ministry of Foreign Affairs and Partners. 2009. Dialogue on adaptation to climate change for land and water management – Draft guiding principles. Copenhagen, Denmark: Danish Ministry of Foreign Affairs.

Dasgupta, S.; Laplante, B.; Meisner, C.; Wheeler, D.; Yan, J. 2007. *The impact of sea-level rise on developing countries: A comparative analysis*. World Bank Policy Research Working Paper 4136. Washington, DC: World Bank.

de Fraiture, C.; Giordano, M.; Liao, Y. 2008. Biofuels and implications for agricultural water use: Blue impacts of green energy. *Water Policy* 10 (Supplement I): 67-81.

Denier van der Gon, H.A.C.; Kropff, M.J.; van Breemen, N.; Wassmann, R.; Lantin, R.S.; Aduna, E.; Corton, T.M.; van Laar, H.H. 2002. Optimizing grain yields reduces CH_4 emissions from rice paddy fields. *Proc. Natl. Acad. Sci. USA* 99: 12021-12024.

Department of Fisheries, Thailand. 2009. *http://www.fisheries.go.th/it-stat/* (accessed March 2009).

Dery, P.; Anderson, B. 2007. Peak phosphorus. Energy Bulletin. *http://www.energybulletin.net/node/33164* (accessed May 2009).

de Silva, S.S.; Soto, D. 2008. Climate change and aquaculture: Potential impacts, adaptation and mitigation. In: *Climate change implications for fisheries and aquaculture: Overview of current scientific knowledge*, ed. Cochrane, K.; Young, C. De; Soto, D. Fisheries Technical Paper. Rome: FAO. 215p.

Dugan, P. 2008. Mainstream dams as barriers to fish migration: International learning and implications for the Mekong. *Catch and Culture* 14(3). Vientiane, Lao PDR: MRC. *http://www.mrcmekong.org/Catch-Culture/vol14_3Dec08/mainstream-dams-barriers.htm*

Earthtrends. 2009. Online database. *http://earthtrends.wri.org/searchable_db/*

Eastham, J.; Mpelasoka, F.; Mainuddin, M.; Ticehurst, C.; Dyce, P.; Hodgson, G.; Ali, R.; Kirby, M. 2008. *Mekong river basin water resources assessment: Impacts of climate change*. Water for a Healthy Country National Research Flagship. Canberra, Australia: CSIRO (Commonwealth Scientific and Industrial Research Organisation), 153p.

Economist. 2008. *http://www.economist.com/world/asia/displaystory.cfm?story_id=13527987* (accessed April 2009).

Evans, P.T.; Marshke, M.; Paudyal, K. 2004. *Flood forest, fish and fishing villages*. Philippines: Asia Forest Network. *http://www.asiaforestnetwork.org/pub/pub49.pdf (accessed April 2009)*.

Facon, T. 2007. Performance of irrigation and participatory irrigation management: Lessons from FAO's irrigation modernization program in Asia. *http://www.vncold.vn/Modules/CMS/Upload/13/Documents/PIMfaconEW_19_10_07/PIMfaconEW.pdf*

Falkenmark, M.; Widstrand, C. 1992. Population and water resources: A delicate balance. *Population Bulletin*. 47(3): 1-36. Washington: Population Reference Bureau.

FAO (Food and Agriculture Organization of the United Nations). 2008. Digital agricultural atlas of Myanmar. *http://dwms.fao.org/atlases/myanmar/index_en.htm*

FAO. 2009a. AQUASTAT database. Available at http://www.fao.org/nr/water/aquastat/main/index.stm

FAO. 2009b. FAOSTAT database. Available at http://faostat.fao.org

FAO. 2009c. TerraStat database. Available at http://www.fao.org/ag/agl/agll/terrastat/wsr.asp#terrastatdb

Fischer, G.; Shah, M.; van Velthuizen, H. 2002. *Climate change and agricultural vulnerability*. Johannesburg: Preprints, World Summit on Sustainable Development, 160p.

Foley, J.; DeFries, R.; Asner, G.P.; Barford, C.; Bonan, G.; Carpenter, S.R.; Stuart Chapin, F.; Coe, M.T.; Daily, G.C.; Gibbs, H.K.; Helkowski, J.H.; Holloway, T.; Howard, E.A.; Kucharik, C.J.; Monfreda, C.; Patz, J.A.; Colin Prentice, I.; Ramankutty, N.; Snyder, P.K. 2005. Global consequences of land use. *Science* 309(5734): 570-74.

Fowler, R.; Rockström, J. 2001. Conservation tillage for sustainable agriculture—an agrarian revolution gathers momentum in Africa. *Soil Till. Res*. 61: 93-107.

Friend, R.M.; Blake, D.J.H. 2009. Negotiating trade-offs in water resources development in the Mekong basin: Implications for fisheries and fishery-based livelihoods. *Water Policy* 11(S1): 13-30.

Friend, R.M.; Suparerk Janprasart; Sobsan Petchkam; Blake, D.J.H. 2006. Climate change vulnerability and adaptation in the Songkhram river basin. Wetlands Biodiversity Conservation and Sustainable Use Programme. http://www.mekongwetlands.org/ (accessed May 2009).

Frink, C.R.I.; Waggoner, P.E.; Ausubel, J.H. 1999. Nitrogen fertilizer: Retrospect and prospect. *Proc. Natl. Acad. Sci. USA* 96: 1175-1180.

Galloway, J.N.; Dentener, F.J.; Capone, D.G.; Boyer, E.W.; Howarth, R.W.; Seitzinger, S.P.; Asner, G.P.; Cleveland, C.; Green, P.A.; Holland, E.; Karl, D.M.; Michaels, A.; Porter, J.H.; Townsend, A.; Vorosmarty, C. 2004. Nitrogen cycles: Past, present, and future. *Biogeochemistry* 70: 153-226.

Galloway, J.N.; Townsend, A.R.; Erisman, J.W.; Bekunda, M.; Cai, Z.; Freney, J.R.; Martinelli, L.A.; Seitzinger, S.P.; Sutton, M.A. 2008. Transformation of the Nitrogen Cycle: Recent trends, questions, and potential solutions. *Science* 320(5878): 889-892.

GCP (Global Carbon Project). 2008. Carbon budget and trends 2007. Global Carbon Project http://www.globalcarbonproject.org

GERES. 2009. http://www.geres-cambodia.org/appropriate.php (accessed September 2009).

Government Statistical Office of Vietnam. 2009. http://www.gso.gov.vn/

Gowing, J.W.; Tuong, T.P.; Hoanh, C.T.; Kheim, N.T. 2006. Social and environmental impact of rapid change in the coastal zone of Vietnam: An assessment of sustainability issues. In: *Environment and livelihoods in tropical coastal zones: Managing agriculture-fishery aquaculture conflicts*, ed. Hoanh, C.T.; Tuong, T.P.; Gowing, J.W.; Hardy, B. UK: CABI.

Halls, A.S.; Kirkwood, G.P.; Payne, A.I. 2001. A dynamic pool model for floodplain-river fisheries. *Ecohydrology and Hydrobiology* 1(3): 323-339.

Halls, A.S.; Kshatriya, M. 2009. Modelling the cumulative effects of mainstream hydropower dams on migratory fish populations in the lower Mekong basin. Draft Report to the Mekong River Commission Secretariat, March 2009.

Hang, P.T.; Lennaerts, T. 2008. Joint basin development planning to foster IWRM in the Lower Mekong basin. Paper presented to the Symposium, Mekong Management at a Watershed-WRM in the Global Crisis? 29 September-1 October 2008, Gothenburg University, Sweden. http://www.mrcmekong.org/programmes/bdp/bdp-publication.htm

Hasegawa, T. 2006. *Response of rice to increasing* CO_2 *and temperature: Recent findings from large-scale FACE experiments and future research priorities*. Climate Change and Rice Planning Workshop, March 2006. Los Banos, Philippines: International Rice Research Institute (IRRI).

Hien, H.M. 2008. Climate change and variability assessment: Agricultural implication in Vietnam. Paper presented at the International Symposium on Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences 2008, Hanoi, Vietnam, December 4-6, 2008.

Hirabayashi, Y.; Kanae, S.; Emori, S.; Oki, T.; Kimoto, M. 2008. Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Sciences Journal* 53(4): 754-772.

Hoanh, C.T.; Guttman, H.; Droogers, P.; Aerts, J. 2003. ADAPT. *Water, climate, food and environment under climate change. The Mekong basin in Southeast Asia*. Colombo: International Water Management Institute; Phnom-Penh: Mekong River Commission; Wageningen: Future Water, Institute of Environmental Studies, 59p.

Hoanh, C.T.; Guttman, H.; Droogers, P.; Aerts, J. 2004. Will we produce sufficient food under climate change? Mekong Basin (South East Asia). Chapter 8. In: *Climate change in contrasting river basins: Adaptation strategies for water, food and environment*, ed. Aerts, J.; Droogers, P. UK: CABI.

Hobbs, P.R. 2007. Conservation agriculture: What is it and why is it important for future sustainable food production? *J. Agric. Sci*. 145: 127-137.

Hortle, K.G. 2007. Consumption and the yield of fish and other aquatic animals from the lower Mekong basin. *MRC Technical Paper* 16: 1-88.

Hortle, K.G.; Lieng, S.; Valbo-Jorgensen, J. 2004. *An introduction to Cambodia's inland fisheries*. Mekong Development Series No. 4. Phnom Penh, Cambodia: Mekong River Commission, 41p.

Howarth, R.W.; Bringezu, S.; Bekunda, M.; de Fraiture, C.; Maene, L.; Martinelli, L.; Sala, O. 2009. Rapid assessment on biofuels and environment: Overview and key findings. In: *Biofuels: Environmental consequences and interactions with changing land use, Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach, Germany*, ed. Howarth, R.W.; Bringezu, S. 1-13. Ithaca NY, USA: Cornell University.

International Rivers. 2009. www.internationalrivers.org/files/ChineseOverseasDams0409.xls

IPCC (Intergovernmental Panel on Climate Change). 2000. *IPCC special report – Emission scenarios. Summary for policymakers*. A Special Report of IPCC Working Group III published for the Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK; New York, USA: Cambridge University Press.

IPCC. 2007. *Climate change 2007: Synthesis report*. An assessment of the Intergovernmental Panel on Climate Change. Cambridge, UK; New York, USA: Cambridge University Press.

IRN (International Rivers Network). 2009a. http://internationalrivers.org/en/china/tiger-leaping-gorge-dam

IRN. 2009b. http://internationalrivers.org/en/china/nu-salween-river

Irrawaddy. 2009. http://www.irrawaddy.org/article.php?art_id=10064

IRRI (International Rice Research Institute). 2008. The rice crisis: *What needs to be done*? IRRI Briefing Note. Manila, Philippines: IRRI.

IRRI. 2009. Flood proof rice. http://www.irri.org/flood-proof-rice/ (accessed September 2009).

IUCN (International Union for the Conservation of Nature); IWMI (International Water Management Institute); Ramsar Convention on Wetlands; WRI (World Resources Institute). 2003a. *Watersheds of Asia and Oceania.* AS12 Irrawaddy. Water Resources eAtlas.

IUCN; IWMI; Ramsar; WRI. 2003b. *Watersheds of Asia and Oceania*. AS19 Mekong. Water Resources eAtlas.

IUCN; IWMI; Ramsar; WRI. 2003c. *Watersheds of Asia and Oceania*. AS23 Salween. Water Resources eAtlas.

IWMI (International Water Management Institute). 2006. *Agricultural water management technologies for small-scale farmers in southern Africa: An inventory and assessment of experiences, good practices and costs*. Final report for OFDA and USAID. Pretoria: Southern Africa Sub-Regional Office, IWMI.

Jayanthi, C.; Rangasamy, A.; Chinnusamy, C. 2000. Water budgeting for components in lowland integrated farming systems. *Agricultural Journal* 87(7/9): 411-414.

Jianchu, X.; Shrestha, A.; Vaidya, R.; Eriksson, M.; Hewitt, K. 2007. *The melting Himalayas. Regional challenges and local impacts of climate change on mountain ecosystems and livelihoods*. Kathmandu: International Centre for Integrated Mountain Development.

Johnston, R.; Hoanh, Chu Thai; Lacombe, G.; Noble, A.; Smakhtin, V.; Suhardiman, D.; Pheng, Kam Suan; Sze, Choo Poh. 2009. Scoping study on natural resources and climate change in Southeast Asia with a focus on agriculture. Report prepared for the Swedish International Development Agency. Vientiane, Lao PDR: International Water Management Institute, Southeast Asia. IWMI-SEA.

Jones, R.G.; Noguer, M.; Hassell, D.C.; Hudson, D.; Wilson, S.S.; Jenkins, G.J.; Mitchell, J.F.B. 2004. *Generating high resolution climate change scenarios using PRECIS*. Met Office Hadley Centre. April 2004. Exeter: R. Taylor, 40p.

Jung, A. 2008. Phosphate industry outlook. http://www.firt.org/Presentation_Archive/2008/JOINT/Jung_Phosphate_Outlook_presentation.pdf (accessed May 2009).

Kazama, S.; Muto, Y.; Nakatsuji, K.; Inoue, K. 2002. Study on the 2000 flood in the Lower Mekong by field survey and numerical simulation. *Proc. 13th Congress APD/IAHR*, 1: 534-539 (2002).

Kiem, A.S.; Ishidaira, H.; Hapuarachchi, H.P.; Zho, M.C.; Hirabayashi, Y.; Takeuchi, K. 2008. Future hydroclimatology of the Mekong river basin simulated using the high resolution Japan Meteorological Agency (JMA) AGCM. *Hydrological Processes* 22: 1382-1394.

King, J.; Brown, C.; Sabet, H. 2003. A scenario-based holistic approach to environmental flow assessments for rivers. *River Research and Applications* 19: 619-639.

King, P.; Bird, J.; Haas, L. 2007. The current status of environmental criteria for hydropower development in the Mekong region: A literature compilation. Consultants Report to ADB (Asian Development Bank), MRCS (Mekong River Commission Secretariat); WWF (World Wide Fund for Nature). Vientiane, Lao PDR (Duplicated).

Krittasudthacheewa, C.; Apirumanekul, C. 2008. Change of hydrology and fishery impacts in the Tonle Sap. Chapter 1 In: *Sustaining Tonle Sap*: *An assessment of development challenges facing the Great Lake*, ed. Chadwick, M.; Juntopas, M.; Sithirith, M. Bangkok: Sustainable Mekong Research Network (Sumernet), 144p.

Kummu, M.; Sarkkula, J. 2008. Impact of the Mekong River flow alteration on the Tonle Sap flood pulse. *Ambio* 37(3).

Kummu, M.; Varis, O. 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong river. *Geomorphology* 85(2007): 275-293.

Lazarus, K. 2009. *In search of aluminum: China's role in the Mekong region*. Cambodia: Heinrich Böll Stiftung; Denmark: WWF; Canada: International Institute for Sustainable Development, 38p.

Mac Sweeney, C.; New, M.; Lizcano, G. 2008a. *UNDP climate change country profiles*: Cambodia. School of Geography and the Environment of the University of Oxford. Oxford: United Nations Development Programme (UNDP), 27p.

Mac Sweeney, C.; New, M.; Lizcano, G. 2008b. *UNDP climate change country profiles*: *Documentation*. School of Geography and the Environment of the University of Oxford. Oxford: UNDP, 18p.

Mac Sweeney, C.; New, M.; Lizcano, G. 2008c. *UNDP climate change country profiles*: Vietnam. School of Geography and the Environment of the University of Oxford. Oxford: UNDP, 27p.

MAFF (Ministry of Agriculture, Forestry and Fisheries). 2009a. *Economic land concession in Cambodia*. Cambodia: Ministry of Agriculture, Forestry and Fisheries. http://www.elc.maff.gov.kh/

MAFF. 2009b. Agricultural statistics, available online at Ministry of Agriculture, Forestry and Fisheries, Cambodia.

MAFF; MOWRAM (Cambodian Ministry of Agriculture, Forestry and Fisheries; Cambodian Ministry of Water Resources and Management). 2007. *Agriculture and water strategy 2006-2010*. Phnom Penh: Royal Government of Cambodia. http://www.fadinap.org/cambodia/agricstat20002001.htm

Mainuddin, M.; Kirby, M.; Chen, Y. 2008. *Spatial and temporal pattern of land and water productivity in the Lower Mekong river basin*. CGIAR Challenge Program for Food and Water. Basin Focal Project Working Paper No. 5. Colombo, Sri Lanka: CGIAR. http://www.waterandfood.org/fileadmin/CPWF_Documents/Documents/Basin_Focal_Projects/BFP_Publications/Spatial_Temporal_Pattern_Land_Water_Productivity_Mekong_BFPWP5_pgs1-21.pdf

McCartney, M. 2009. Living with dams: Managing the environmental impacts. *Water Policy* 11 Supplement 1 (2009): 121-139.

McCartney, M.; Rebelo, L.M.; Senaratna Sellamuttu, S.; de Silva, S.; Masiyandima, M. (in press) *Wetlands, agriculture and poverty alleviation: Appropriate management to safeguard and enhance wetland productivity*. To be published as an IWMI Research Report. Colombo, Sri Lanka.

McGray, H.; Hammill, A.; Bradley, R. 2007. *Weathering the storm: Options for framing adaptation and development*. Washington, DC: World Resources Institute. Online at http://www.wri.org/publication/weathering-the-storm

Messerli, P.; Heinimann, A.; Epprecht, M.; Phonesaly, S.; Thiraka, C., Minot, N., eds. 2008. *Socio-economic atlas of the Lao PDR—An analysis based on the 2005 Population and Housing Census*. Swiss National Center of Competence in Research (NCCR) North-South. Bern: University of Bern; Vientiane: Geographica Bernensia.

Milly, P.C.D.; Bettancourt, J.; Falkenmark, M.; Hirsch, R.M.; Kundzewicz, Z.W.; Lettenmaier, D.P.; Stouffer, R.J. 2008. Stationarity is dead: Whither water management? *Science* v(319): 573-4.

MoE (Ministry of Environment). 2005. *Cambodia National Adaptation Program of Action (NAPA) to climate change*. Phnom Penh, Cambodia: MoE.

Molle, F.; Floch, P. 2008. Megaprojects and social and environmental changes: The case of the Thai "water grid." *Ambio*. 37(3): 199-204.

Molle, F. 2004. Technical and institutional responses to basin closure in the Chao Phraya river basin, Thailand. *Water International* 29(1): 70-80.

MONRE (Ministry of Natural Resources and Environment). 2008. Vietnam National Adaptation Program of Action (NAPA) to climate change. Unofficial translation of Vietnamese draft version of 27 July 2008.

MONRE. 2009. http://www.monre.gov.vn/MONRENET/default.aspx?tabid=255&idmid=&ItemID=66584

Morton, P. 2008. Scoping study: Options for reducing greenhouse gas emissions in Vietnam, Lao PDR and Cambodia. Final report to AusAID, Mekong and Regional. Bangkok (Duplicated).

MPI (Ministry of Planning and Investment). 2008. *Approved foreign investment by country and sector 2001 - January 2008 in Lao PDR.* Vientiane, Lao PDR: Government of Lao PDR.

MRC (Mekong River Commission). 2003. *State of the basin report*. Phnom Penh, Cambodia: MRC.

MRC. 2005. *Overview of the hydrology of the Mekong basin*. Vientiane: MRC, November 2005.

MRC. 2009a. Map of planned hydropower projects in the Lower Mekong Basin http://www.mrcmekong.org/download/programmes/hydropower/Map%20LMB%20Hydroprojects%20%2B10Mw%200208.jpg

MRC. 2009b. *Mekong River Commission climate change and adaptation initiative*. Framework document for implementation and management. Vientiane, Lao PDR: MRC.

MRC. 2010. *State of the Basin Report 2010*. Vientiane, Lao PDR: Mekong River Commission,

MRC; UNEP (United Nations Environmental Programme). 1997. *Mekong river basin diagnostic study*. Final Report. Bangkok.

MRCS/IBFM (Mekong River Commission Secretariat/Integrated Basin Flow Management). 2006. *Flow regime assessment*. Integrated Basin Flow Management. Report No. 8. Vientiane: MRCS, 93p.

MRC-TNMC (Mekong River Commission-Thailand National Mekong Committee). 2004. *Report: Analysis of sub-area 5T, basin development plan*. Mekong River Commission, Thailand National Mekong Committee. Unpublished report to MRC.

MRC-VNMC (Mekong River Commission-Vietnam National Mekong Committee). 2004. *Report: Analysis of sub-area 10V, basin development plan*. Mekong River Commission - Vietnam National Mekong Committee. http://www.mrcmekong.org/download/programmes/bdp/VNMC-0311-SA-10V.pdf

Mukherji, A.; Facon, T.; Burke, J.; de Fraiture, C.; Faurès, J.-M.; Füleki, B.; Giordano, M.; Molden, D.; Shah, T. 2009. *Revitalizing Asia's irrigation: To sustainably meet tomorrow's food needs*. Colombo, Sri Lanka: IWMI; Rome, Italy: FAO.

Naing, M.M. 2005. *Paddy field irrigation systems in Myanmar. Proceedings of the regional workshop on the future of large rice-based irrigation systems in Southeast Asia, Ho Chi Minh City, Vietnam, 26–28 October 2005.*

Nesbitt, H.J. 2005. *Water used for agriculture in the Lower Mekong basin*. MRC Working Paper. Vientiane, Lao PDR: MRC.

Nguyen Thi Kim Thoa; Arduino, G.; Bono, P.; Nguyen Van Giang; Phan Thi Kim Van; Bui Tran Vuong. 2008. Management of aquifer recharge: Groundwater storage in the sand dunes of Vietnam. *Tech. Monitor* (Sept.-Oct. 2008): 31-37.

Noble, A.D.; Suzuki, S. 2005. Improving the productivity of degraded cropping systems in Northeast Thailand: Improving farmer practices with innovative approaches. PAWEES 2005 International Conference, Kyoto, Japan, September. see http://www.iwmi.cgiar.org/Publications/Annual Publication Lists/forms/Invited Papers 2005.html

NWC (National Water Commission). 2009. *Australian guidelines for water recycling: Managed aquifer recharge*. National Water Quality Management Strategy Document No 24, July 2009. Canberra: NWC.

Paydar, Z.; Khan, S.; Jamnani, M.A.R.; Blackwell, J. 2007. *Regional land suitability guidelines for SBC "Serial Biological Concentration" application*. CSIRO Land and Water Science Report 46/07. Canberra: Commonwealth Scientific and Industrial Research Organisation.

Pech, S.; Sunada, K. 2008. Population growth and natural-resources pressures in the Mekong River Basin. *Ambio* 37(3): 219-224.

Phan, T.L.; Pham, M.P.; Visser, T.; Sjorslev, J.G.; Hortle, K.H. 2003. Inland fisheries activities and fish consumption in Tra Vinh Province, Vietnam. *MRC Conference Series* 4: 127-139. www.mrcmekong.org

Phien-wej, N.; Giao, P.H.; Nutalaya, P. 2006. Land subsidence in Bangkok, Thailand. *Engineering Geology* 82(4): 187-201.

Pingali, P. 2004. *Westernization of Asian diets and the transformation of food systems: Implications for research and policy*. ESA Working Paper No. 04-17. Rome, Italy: Economic and Social Department, FAO.

Poff, N.L.; Richter, B.; Arthington, A.; Bunn, S.; Naiman, R.; Kendy, E.; Acreman, M.; Apse, C.; Bledsoe, B.; Freeman, M.; Henriksen, J.; Jacobson, R.; Kennen, J.; Merritt, D.; O'Keeffe, J.; Olden, J.; Rogers, K.; Tharme, R.; Warner, A. 2009. The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. *Freshwater Biology* 2009. Available on-line at http://rydberg.biology.colostate.edu/~poff/Public/poffpubs/Poff_etal_2009_eloha_FWB.pdf (accessed September 2009).

Poulsen, Anders; Poeu, Ouch; Viravong, Sintavong; Suntornratana, Ubolratana; Thanh Tung, Nguyen. 2002. *Deep pools as dry season fish habitats in the Mekong basin*. MRC Technical Paper No. 4. Phnom Penh: Mekong River Commission, 22p.

Raksmey, M.; Jinno, K.; Tsutsumi, T. 2009. Effects of river water on groundwater in Cambodia. *Memoirs of the Faculty of Engineering, Kyushu University* 69(3): September 2009.

Ramnarong, V.; Buapeng, S. 1992. Groundwater resources of Bangkok and its vicinity: Impact and management. In: *Proc. National Conf. Geol. Res. Thailand: Potential for future development*, 172-184. Bangkok: Department of Mineral Resources.

Ramsar. 2009. Ramsar sites database. http://ramsar.wetlands.org/

Raschid-Sally, L.; Jayakody, P. 2008. *Drivers and characteristics of wastewater agriculture in developing countries: Results from a global assessment*. IWMI Research Report 127. Colombo, Sri Lanka: IWMI, 35p.

Resurreccion, B.P.; Sajor, E.E.; Fajber, E. 2008. *Climate adaptation in Asia: Knowledge gaps and research issues in South East Asia*. Kathmandu, Nepal: ISET-International and ISET-Nepal, 76p.

Richter, B.; Warner, A.; Meyerc, J.; Lutz, K. 2006. A collaborative and adaptive process for developing environmental flow recommendations. *River Res. Applic*. 22: 297-318.

Roeckner, E.; Arpe, K.; Bengtsson, L.; Christoph, M.; Claussen, M.; Dumenil, L.; Esch, M.; Giorgetta, M.; Schlese, U.; Schulzweida, U. 1996. *The atmospheric general circulation model ECHAM4: Model description and simulation of present-day climate*. Hamburg, Germany: Max Planck Institut für Meteorologie.

Ruosteenoja, K.; Carter, T.R.; Jylhä, K.; Tuomenvirta, H. 2003. *Future climate in world regions: An intercomparison of model-based projections for the new IPCC emissions scenarios*. Helsinki: Finnish Environment Institute, 81p.

Rutherford, J.; Lazarus, K.; Kelley, S. 2008. *Rethinking investments in natural resources: China's emerging role in the Mekong region*. Phnom Penh, Cambodia: Heinrich Böll Stiftung, WWF and International Institute for Sustainable Development.

Ryvitski, J.P.M.; Kettner, A.J.; Overeem, I.; Hutton, E.W.H.; Hannon, M.T.; Brakenridge, G.R.; Day, J.; Vörösmarty, C.; Saito, Y.; Giosan, L.; Nicholls, R.J. 2009. Sinking deltas due to human activities. *Nature Geosciences*. Published online: 20 September 2009.

Saraphirom, P. 2009. *Ecohydrologic approach for sustainable water and land resources management in salt affected area under climatic variability and change conditions. Proceedings of Workshop on "The Management of Surface and Groundwater Resources and Environment for the Decade 2010' held on 29 September 2009*. Thailand: Ground Water Research Center, Khon Kaen University.

Sass, R.L.; Fisher, F.M.; Harcombe, P.A.; Turner, F.T. 1991. Mitigation of methane emissions from rice fields: Possible adverse effects of incorporated rice straw. *Global Biogeochem*. *Cycles* 5(3): 275-287.

SCW (Save Cambodia's Wildlife). 2006. Atlas of Cambodia: *National poverty and environment maps*. Phnom Penh, Cambodia: Save Cambodia's Wildlife.

Setboonsarng, S.; Gilman, J. 2009. *Alternative agriculture in Thailand and Japan*. Bangkok, Thailand: School of Environment Resources and Development, Asian Institute of Technology. http://www.solutions-site.org/cat11_sol85.htm

Shah, T. 2009. *Taming the anarchy: Groundwater governance in South Asia*. Washington, DC, USA: RFF Press.

Sinath, C. 2001. *Investment in land and water in Cambodia*. Phnom Penh, Cambodia: Irrigated Agriculture Department, Ministry of Water Resources and Meteorology.

Sithirith, M.; Mathur, V. 2008. Entitlements and the community fishery in the Tonle Sap: Is the fishing lot system still an option for the fisheries management? In: *Sustaining Tonle Sap: An assessment of development challenges facing the Great Lake*, ed. Chadwick, M.; Juntapos, M.; Sithirith, M.; Bangkok: Sustainable Mekong Research Network (Sumernet). 114p. ISBN 978-91-86125-06-6.

Smakhtin, V.; Das, S.; Arunachalam, M.; Sivaramakrishnan, K.G.; Unni, K.S.; Joshi, G.; Chatterjee, A.; Behera, S.; Gautam, P. 2007. *An assessment of ecological value and condition of India river basins for estimation of environmental water demand.* IWMI Research Report 114. Colombo, Sri Lanka: IWMI.

Smakhtin, V.U.; Eriyagama, N. 2008. Developing a software package for global desktop assessment of environmental flows. *Environmental Modelling & Software* 23: 1396-1406.

Smith, P.; Martino, D.; Cai, Z.; Gwary, D.; Janzen, H.; Kumar, P.; McCarl, B.; Ogle, S.; O'Mara, F.; Rice, C.; Scholes, B.; Sirotenko, O. 2007. Agriculture. In: *Climate change 2007: Mitigation, contribution of working group iii to the fourth assessment report of the intergovernmental panel on climate change*, ed. Metz, B.; Davidson, O.R.; Bosch, P.R.; Dave, R.; Meyer, L.A. UK: Cambridge; New York, NY, USA: Cambridge University Press United.

Snidvongs, A.; Choowaew, S.; Chinvanno, S. 2003. *Impact of climate change on water and wetland resources in Mekong river basin: Directions for preparedness and action*. Bangkok: IUCN and Southeast Asia START Regional Center, 54p.

Soe, K.M. 2008. *Trends of development of Myanmar fisheries: With references to Japanese experiences*. Visiting Research Fellow Monograph Series No. 433. Wakaba, Japan: Institute of Developing Economies, Japan External Trade Organization, 58p.

Srisuk, K.; Chusanatus, S.; Boonsongka, P.; Sarapirom, P.; Archwichai, L.; Pavelic, P. Forthcoming. Hydrogeological mapping of managed aquifer recharge potential in the Lower Yom River Basin, Thailand. Paper to be presented at the 38th IAH Congress, Krakow, Poland, September 2010.

Starr, C.M. 2003. Fishing lots and people in Cambodia. In: *Social challenges of the Mekong region*, ed. Kaosa-ard, M.; Dore, J., 347-367. Bangkok: White Lotus.

Steinfeld, H.; Gerber, P.; Wassenaar, T.; Castel, V.; Rosales, M.; de Haan, C. 2006. *Livestock's long shadow: Environmental issues and options*. Rome: FAO.

Sugiyama, S.; Staples, D.; Funge-Smith, S. 2004. *Status and potential of fisheries and aquaculture in Asia and the Pacific*. RAP Publication 2004/25. Bangkok: FAO, Regional Office for Asia and the Pacific, 53p.

Sun, Ge; Zhou, Guoyi Zhou; Zhiqiang; Wei, Xiaohua; McNulty, Steven G.; Vose, James M. 2006. Potential water yield reduction due to forestation across China, *Journal of Hydrology* 328 (3-4): 548-558. ICWRER - Symposium in Dresden, Germany.

SWH (Swedish Water House). 2009. *Securing water for ecosystems and human well-being: The importance of environmental flows*. Stockholm, Sweden: Swedish Water House, 52p.

Thanh, T.D.; Saito, Y.; Huy, D.V.; Nguyen, V.L.; Ta, T.K.O.; Tateishi, M. 2004. Regimes of human and climate impacts on coastal changes in Vietnam. *Reg. Environ. Change* 4: 49-62.

Theuambounmy, H. 2007. Status of renewable energy development in the Lao People's Democratic Republic. Paper presented at ESCAP/Green Growth meeting on Greening Business and Making Environment a Business Opportunity. Bangkok, Thailand, June 2007.

TKK (Helsinki University of Technology); SEA START RC (Southeast Asia START Regional Center). 2009. *Water and climate change in the Lower Mekong basin: Diagnosis and recommendations for adaptation*. Water and Development Research Group, Helsinki University of Technology (TKK), and Southeast Asia START Regional Center (SEA START RC). Espoo, Finland: Chulalongkorn University. Water & Development Publications, Helsinki University of Technology.

Tuan, L.A.; Hoanh, C.T.; Miller, F.; Sinh, B.T. 2007. Flood and salinity management in the Mekong delta, Vietnam. In: *Challenges to sustainable development in the Mekong delta: Regional and national policy issues and research needs*, ed. Be, T.T.; Miller, F.; Sinh, B.T. The Sustainable Mekong Research Network (Sumernet). Bangkok, Thailand: Stockholm Environment Institute (SEI) – Asia..

UNDP (United Nations Development Programme). 2006. *Myanmar agricultural sector review and investment strategy volume 1*. United Nations Development Programme http://www.mm.undp.org/UNDP_Publication_PDF/ASR%20Vol.2%20Investment%20Strategy.pdf

UNDP. 2008. *Residential energy demand in rural Cambodia - an empirical study for Kampong Speu and Svay Rieng*. Phnom Penh, Cambodia: UNDP Cambodia.

UNEP; TEI (United Nations Environment Programme; Thailand Environment Institute). 2007. *Greater Mekong environment outlook 2007*. Bangkok: UNEP; TEI, 122p.

USDA FAS (United States Department of Agriculture Foreign Agricultural Service). 2006. http://www.fas.usda.gov/info/fasworldwide/2006/09-2006/ChinaBiofuels.pdf

USDA FAS. 2007 http://www.fas.usda.gov/gainfiles/200706/146291285.pdf

Valentin, C.; Agus F.; Alamban, R.; Boosaner, A.; Bricquet, J.P.; Chaplot, V.; de Guzman, T.; de Rouw, A.; Janeau, J.L.; Orange, D.; Phachomphonh, K.; Phai Do; Podwojewski, P.; Ribolzi, O.; Silvera, N.; Subagyono, K.; Thiébaux, J.; Toan, T.; Vadari, T. 2008. Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices. *Agriculture, Ecosystems and Environment* 128: 225-238.

van der Mheen, H. 1999. Observations on the integration of aquaculture and small-scale irrigation. *FAO Aquaculture Newsletter* 22:10-15. Rome: FAO.

van Zalinge, N.; Degen, P.; Pongsri, C.; Nuov, S.; Jensen, J.G.; Nguyen, V.H.; Choulamany, X. 2004. The Mekong river system. In: *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries: Sustaining Livelihoods and Biodiversity in the New Millennium* Vol. 1. ed. Welcomme, R.L.; Petr, T. RAP Publication 2004/16. http://www.fao.org/docrep/007/ad525e/ad525e0l.htm#bm21

Vickers, B. 2009. REDD in Southeast Asia. Paper presented to Sida-SENSA Retreat, Kunming, March 2009.

Voladet, S. 2008. *Sustainable development in the plantation industry in Lao PDR: An examination of the role of the Ministry of Planning and Investment*. Winnipeg, Canada: International Institute for Sustainable Development, 34p.

Wassmann, R.; Hien, N.X.; Hoanh, C.T.: Tuong, T.P. 2004. Sea-level rise affecting the Vietnamese Mekong delta: Water elevation in the flood season and implications for rice production. *Climatic Change* 66: 89-107.

Water Resources e-Atlas. 2003. *Watersheds of the world CD*. Washington, DC: IUCN, IWMI, Rasmar Convention Bureau and WRI.

WEPA (Water Environment Partnership in Asia). n.d.a. *State of water environmental issues: Lao PDR*. Policies. http://www.wepa-db.net/policies/state/laos/overview.htm. (accessed 19 Nov. 2009).

WEPA. n.d.b. *State of water environmental issues: Vietnam*. Policies: http://www.wepa-db.net/policies/state/Vietnam/overview.htm. (accessed 19 Nov. 2009).

WHO (World Health Organization). 2008. *Institutional collaboration for arsenic mitigation in affected countries in South-East Asia*. Report of an Intercountry Workshop, 11-13 September 2007. Kolkata, India: WHO.

World Bank. 2005. *Towards a more effective operational response arsenic contamination of groundwater in South and East Asian countries* (two volumes). Water and Sanitation Program, Environment and Social Unit, South Asia Region, Report No. 31303. Bangkok: World Bank.

World Bank. 2006. *Re-engaging in agricultural water management: Challenges and options*. Washington, DC: World Bank.

World Bank. 2008. *World Development Report 2008: Agriculture for development*. Washington, DC: World Bank.

World Bank. 2009a. World development indicators. Available online at http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,contentMDK:20535285~menuPK:1192694~pagePK:64133150~piPK:64133175~theSitePK:239419,00.html. (accessed March 2009).

World Bank. 2009b. *East Asia and Pacific Update April 2009: Battling the forces of global recession*. Washington, DC: World Bank.

World Bank. 2009c. The economics of adaptation to climate change: Final methodology report. http://siteresources.worldbank.org/INTCC/Resources/MethodologyReport.pdf

World Commission on Dams. 2000a. Pak Mun dam. WCD Case Study. Report prepared for WCD, Cape Town, South Africa. Accessed on-line at http://www.centre-cired.fr/IMG/pdf/F8_PakMunDam.pdf.

World Commission on Dams. 2000b. *Dams and development: A new framework for decision-making*. London: Earthscan.

WorldFish Center. 2007. *Community-based fisheries management: Capturing the benefits*. Bangladesh. Policy Brief 1. The WorldFish Center WF PB#8 (http://www.worldfishcenter.org/resource_centre/WF_531.pdf).

World Gazetteer. 2009. http://world-gazetteer.com/

World Water Assessment Programme. 2006. National Water Development Report. Report prepared within the framework of the 2nd phase of the World Water Development Programme 2006. Thailand: World Water Assessment Programme.

WREA (Water Resources and Environment Administration). 2008. Lao PDR National Adaptation Program of Action (NAPA) to Climate Change, August 2008 version.

WRI (World Resources Institute). 2009. World Resources Institute Earthtrends database. http://earthtrends.wri.org/

WWF (World Wildlife Fund). 2009. *The Greater Mekong and climate change: Biodiversity, ecosystem services and development at risk*. Bangkok, Thailand: WWF Greater Mekong Program.

IWMI Research Reports

136 *Climate Change, Water and Agriculture in the Greater Mekong Subregion*. Robyn Johnston, Guillaume Lacombe, Chu Thai Hoanh, Andrew Noble, Paul Pavelic, Vladimir Smakhtin, Diana Suhardiman, Kam Suan Pheng and Choo Poh Sze. 2010.

135 *Impacts of Climate Change on Water Resources and Agriculture in Sri Lanka: A Review and Preliminary Vulnerability Mapping*. Nishadi Eriyagama, Vladimir Smakhtin, Lalith Chandrapala and Karin Fernando. 2010.

134 *Evaluation of Current and Future Water Resources Development in the Lake Tana Basin, Ethiopia*. Matthew McCartney, Tadesse Alemayehu, Abeyu Shiferaw and Seleshi Bekele Awulachew. 2010.

133 *Mapping Drought Patterns and Impacts: A Global Perspective*. Nishadi Eriyagama, Vladimir Smakhtin and Nilantha Gamage. 2009.

132 *Malaria Transmission in the Vicinity of Impounded Water: Evidence from the Koka Reservoir, Ethiopia*. Solomon Kibret, Matthew McCartney, Jonathan Lautze and Gayathree Jayasinghe. 2009.

131 *Implementing Integrated River Basin Management: Lessons from the Red River Basin, Vietnam*. François Molle and Chu Thai Hoanh. 2009.

130 *Economic Gains of Improving Soil Fertility and Water Holding Capacity with Clay Application: The Impact of Soil Remediation Research in Northeast Thailand.* Rathinasamy Maria Saleth, Arlene Inocencio, Andrew Noble and Sawaeng Ruaysoongnern. 2009.

129 *Adaptive Water Resource Management in the South Indian Bhavani Project Command Area*. Mats Lannerstad and David Molden. 2009.

128 *Importance of Irrigated Agriculture to the Ethiopian Economy: Capturing the Direct Net Benefits of Irrigation*. Fitsum Hagos, Godswill Makombe, Regassa E. Namara and Seleshi Bekele Awulachew. 2009.

127 *Drivers and Characteristics of Wastewater Agriculture in Developing Countries: Results from a Global Assessment*. Liqa Raschid-Sally and Priyantha Jayakody. 2008.

126 *Climate Change Impacts on Hydrology and Water Resources of the Upper Blue Nile River Basin, Ethiopia*. Ungtae Kim, Jagath J. Kaluarachchi and Vladimir U. Smakhtin. 2008.

Electronic copies of IWMI's publications are available for free.

Visit

www.iwmi.org/publications/index.aspx

Related Publications

International Water Management Institute (IWMI). 2006. ***Water Figures Asia: news of IWMI's work in Asia***, 1. 7p.

www.iwmi.org/News_Room/Newsletters/Water_Figures/PDFs/WF_ASIA_Issue1.pdf

International Water Management Institute (IWMI). 2006. ***Water governance in the Mekong region: the need for more informed policy-making.*** Colombo, Sri Lanka: International Water Management Institute (IWMI). 6p. (IWMI Water Policy Briefing 022).

www.iwmi.org/Publications/Water_Policy_Briefs/PDF/WPB22.pdf

Johnston, R. M.; Hoanh, C. T.; Lacombe, G.; Noble, A.; Smakhtin, V.; Suhardiman, D.; Kam, S. P.; Choo, P. S. 2010. ***Rethinking agriculture in the Greater Mekong Subregion: how to sustainably meet food needs, enhance ecosystem services and cope with climate change. Summary report.*** Colombo, Sri Lanka: International Water Management Institute (IWMI). 24p.

www.iwmi.org/Publications/Other/PDF/Summary-Rethinking_Agriculture_in_the_Greater_Mekong_Subregion.pdf

Molle, F. 2005. ***Irrigation and water policies in the Mekong region: current discourses and practices.*** Colombo, Sri Lanka: International Water Management Institute (IWMI). 43p. (IWMI Research Report 095).

www.iwmi.org/Publications/IWMI_Research_Reports/PDF/pub095/RR95.pdf

Postal Address
P O Box 2075
Colombo
Sri Lanka

Location
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-11-2880000

Fax
+94-11-2786854

E-mail
iwmi@cgiar.org

Website
www.iwmi.org

IWMI
International
Water Management
Institute

ISSN: 1026-0862
ISBN: 978-92-9090-728-2