WORKING PAPER

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11/2019

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A Scientific Research Agenda for Water Sustainability in the Mekong

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November 13, 2019

ABSTRACT

We present a scientific research agenda for water sustainability of the Mekong River, one of the world's longest river systems, upon which millions of inhabitants depend daily for their basic food security and livelihoods, but which is currently experiencing dramatic modifications, including extensive hydropower development. The 12 research challenges and themes presented here were identified by a diverse team of 24 scientists with expertise in a broad range of scientific disciplines relevant to both the physical and social dimensions of Mekong water sustainability, and were identified during a workshop held in Cambodia sponsored by the US National Science Foundation (NSF). The themes span a comprehensive range of dimensions and describe an integrated research agenda that advocates an interdisciplinary, social-ecological approach. In this paper we present these themes and describe the state of knowledge, and in doing so highlight key research needs and relevant literature. With so many competing water resources needs, addressing these knowledge gaps and finding a way to integrate them into policy and management will be critical for water sustainability in the face of development in the Mekong basin

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation (NSF) under Grant number WSC-1204609. We are grateful to the Center for Khmer Studies (CKS), a member institution of the Council of American Overseas Research Centers, for hosting this workshop in Siem Reap, Cambodia, with particular thanks to Krisna Uk and to Sreypich Tith of CKS. We wish to thank Paige Hutchinson of Florida State University for coordinating NSF funding disbursement. In particular, we wish to thank the other participants in the workshop who provided key insights and comments: Pianporn Deetes; Tracy Farrell; Louise Gallagher; Kimkong Ham; Keavuth Huy; Terek Ketelsen; Jorma Koponen; Matti Kummu; Saran Ly; Chanta Oeurng; Barbara Pollini; Juha Sarkkula; Paradis Someth; Ratha Sor; Nicholas Souter; and Krisna Uk.

INTRODUCTION

The Challenge of Water Sustainability in the Mekong

The Mekong River is one of the world's longest rivers, stretching for more than 4600 km and connecting the countries of China, Myanmar, Lao PDR, Thailand, Cambodia and Vietnam. The river also has levels of biodiversity and biological productivity that are among the highest in the world for freshwater ecosystems (Hortle 2007; Rainboth 1996; Bonhuer 2001; Coates et al. 2003; Campbell et al. 2006a; Sverdrup-Jensen 2002). The natural flood-pulse hydrological system of the Mekong River creates an annually fluctuating regime of water availability and quality, combined with high annual sediment loads and nutrient fluxes, that has provided multiple ecosystem services for ~5,000 years (Day et al. 2011). The Mekong region is also exceptional in its human dependence on the river. The Tonle Sap lake in the lower Mekong is a UNESCO Biosphere Reserve that supports the world's largest inland fishery (Hortle 2007). Rice and fish are the dominant sources of nutrition for over 60 million people in the basin, while several million people in the river basin are directly dependent on wild-caught fish and dryland rice production for livelihoods (Hori 2000; Osborne 2001; Stone 2011). Seasonal river flooding also supports some of the highest rice export volumes in the world, with lower Mekong River countries supplying almost 35% of total global rice exports in 2018 (WTEx 2019). Thus the Mekong seasonal flood pulse is directly responsible for substantial regional and global food security (Smajgl et al. 2015a). Perhaps nowhere else in the world is the daily well-being of local populations as directly dependent upon freshwater biodiversity.

The Mekong annual flood-pulse regime, however, is now being altered at an accelerating pace through economic development and rapid urbanization, the emergence of an extensive hydropower industry, and conversions of land use related to both human activity and climate change (Arias et al. 2012b; Eastham, Mpelasoka, Ticehurst, et al. 2008b; Matti Kummu et al. 2006; Dirk Lamberts and Koponen 2008; Lauri et al. 2012). Currently dozens of hydropower dams and projects have been built or are planned on the Mekong and its upstream tributaries (E. Baran and Myschowoda 2009). The flood-pulse and river flow are expected to be significantly altered over the next several decades from these changes, potentially reducing floodplain agriculture and fisheries dramatically (Hecht et al. 2019)(Intralawan et al. 2018a; G Mathias Kondolf et al. 2018; Pokhrel et al. 2018a; Stone 2011; Feizizadeh and Blaschke 2013). The most likely hydrological changes caused by upstream damming are reduction of the seasonal river-stage variation, reduction of Tonle Sap lake-level fluctuation, contraction of flooded riparian areas, decrease in groundwater recharge, significant losses in the fishery, and declining capacity of farmers to grow flood-recession and dry-season rice (Västilä et al. 2010; Matti Kummu and Sarkkula 2008c; Matti Kummu et al. 2006). Dams will also alter sediment fluxes, an important source of nutrients on the Cambodian and Vietnamese floodplain ecosystems, (Dirk Lamberts and Koponen 2008) by trapping a significant quantity of Mekong River sediment (M. Kummu et al. 2010).

These changes make this region a "hotspot" of rapid environmental transformation, and one highly vulnerable to climate change. Although downscaling of different Global Circulation Models (GCMs) produce differing results on how the monsoon regime will change in the future, most predict rising temperatures and changing weather patterns that will affect agricultural productivity and fisheries (Christensen et al. 2007; Yusuf and Francisco 2009; Eastham, Mpelasoka, Ticehurst, et al. 2008a; Leary et al. 2012).

The drivers of dramatic change in the Mekong stem from both environmental (e.g. climate change) and social-human (e.g. hydropower, land use change, urbanization, etc.) sources, and the resulting complex, adaptive feedbacks between these changing environmental and social systems defines the Mekong as a complex, regional coupled social-ecological system (L. Lebel et al. 2006). However, the impacts of these hydrological changes on water sustainability, floodplain ecosystem services, and the resilience and adaptability of Mekong coupled social-ecological systems is not well understood (Lambin and Meyfroidt 2010). Despite their importance, Mekong data connecting hydrology to biodiversity, fisheries management, ecosystem services, and livelihoods are sparse, while conceptual frameworks for understanding how physical, biological, and social dynamics in rivers systems create ecosystem services and livelihoods are not well developed (Gerlak, Lautze, and Giordano 2011; Plengsaeng, Wehn, and van der Zaag 2014; Mekong River Commission 2018a). The paucity of models and data limits the ability to predict the effects of widespread ecosystem changes and makes planning for water sustainability intrinsically challenging and interdisciplinary.

A Workshop for a Scientific Research Agenda for Mekong Water Sustainability

Given this context, a coordinated supportive research agenda, focusing on the broader integrated hydrological and biological as well as the human economic, social and behavioral dynamics, is crucially needed and arguably overdue. It was precisely in this context that an international workshop, entitled "Mekong Water Sustainability Research Science", was convened in Siem Reap, Cambodia, funded by the U.S. National Science Foundation (NSF) Water, Sustainability and Climate (WSC) Program, with the aims of considering the interactions, connectivity and interdependence of water systems and ecosystem services in the Lower Mekong to identify a holistic scientific research agenda for supporting Mekong water sustainability.

The Workshop participants were comprised of 24 international experts and scientists on Mekong water sustainability, spanning a wide-range of physical sciences, ecological sciences, and social sciences, including hydrology, ecology, fisheries science, climate change, aquatic biology, ecosystem services modeling, water resources engineering, landscape ecology, remote sensing, geography, planning, anthropology, economics, and sociology. A number of participants are actively managing on-going conservation programs in the Mekong region. Major universities were represented, including those from Europe and North America, but also from The Royal University of Phnom Penh in Cambodia and the Cambodian Institute of Technology. Institutions and non-governmental organizations represented included the Mekong River Commission (MRC), the Cambodian Inland Fisheries Research and Development Institute (IFReDI), Conservation International, World Wide Fund for Nature (WWF), Flora and Fauna International, and The Commonwealth Scientific and Industrial Research Organization (CSIRO). Participants were invited to provide a suite of related interdisciplinary expertise and to comprise a balanced mix of scientists based in or from Southeast Asia as well as from developed countries outside of Asia: physical scientists comprised 62% of the group, while social scientists comprised 38%; 33% were women; 33% were natives of Southeast Asian countries; 46% were university faculty or graduate students, while 54% were from research institutes or NGOs working in the region. A numbr of the participants are employed by large organizations with broad missions and therefore had ready access to colleagues who could assist with the identification of key scientific issues.

Twelve Thematic Areas for Mekong Water Sustainability Research

The process for developing the scientific research agenda began with each individual participant identifying and summarizing key emergent issues for Mekong water sustainability science. The resulting set of 24 issues was circulated among all participants, and discussed in a series of group-wide and break-out sessions to identify key research questions and thematic issues. The result was a distillation to the twelve thematic groupings presented in Table 1. Taken together, they describe a roadmap for a comprehensive scientific research agenda to support Mekong water sustainability, both to improve scientific understanding of its complex social-ecological dynamics, but also to provide a basis for improved planning and policy formation. The twelve thematic groups are organized under three categories: 1) broader considerations; 2) key research areas; and 3) practical foci moving forward. In this article, we discuss each thematic area briefly, followed by a presentation of some conclusive ideas.

Table 1: A Scientific Research Agenda for Water Sustainability for the Mekong River System

Twelve key themes that emerged from an NSF Workshop in Siem Reap, Cambodia
These twelve themes are organized under three categories:

Important Broader Considerations:

Thematic Area #1: *The Importance of Ecosystem Services (ES) as a Research Framework for Mekong water sustainability research*
Thematic Area #2: *The Importance of Interdisciplinary Research*
Thematic Area #3: *The Importance and Utility of Modeling*
Thematic Area #4: *The Importance of Scale*

Specific Crucial Research Areas:

Thematic Area #5: *The Impact of Hydropower and Climate Change*
Thematic Area #6: *The Future of Mekong Aquatic Ecology and Fisheries*
Thematic Area #7: *The Importance of Land-Use Land-Cover Change (LULCC)*
Thematic Area #8: *Research on Mekong Trans-Boundary Governance*
Thematic Area #9: *The Importance of Assessment of Mekong Low-Income Resilience*
Thematic Area #10: *Additional Considerations Pertaining to Mekong Scientific Data*

Key Practical Foci Moving Forward:

Thematic Area #11: *The Importance of Stakeholder Engagement and Participatory Planning*
Thematic Area #12: *Bridging the Gaps Between Scientific Research and The Domain of Policy Making; Improving Effective Communication and Engagement From the Research Community to Policy Makers*

IMPORTANT BROADER CONSIDERATIONS

Thematic Area 1: The Importance of Ecosystem Services as a Research Framework for Mekong Water Sustainability

A consensus of the workshop was the importance of an ecosystem services framework for assessing the social-ecological dimensions of Mekong water sustainability, and as an important framework for linking scientific understanding of ecological and biological systems to planning and policy decisions. The identification, measurement, and economic valuation of ecosystem services are essential in translating research findings to decision-making outcomes. For example, an integrated ecosystem service framework can link system hydrology, vegetation, agricultural and fish productivity with human activity, resulting in models of tradeoffs and interaction, which can be used to develop projections of impacts based on varying climate and development scenarios.

Mekong hydrology provides ecosystem services through direct uses such as agricultural, fish and forest products, and indirectly for health and overall wellbeing (D Lamberts 2006; Loc et al. 2016; WWF (World Wide Fund for Nature) 2013). Specifically, these services include: the transport of energy and biomass; connectivity of land and water for farming and fishing; natural irrigation and drainage; water supply for agriculture; maintenance of floodplains and wetlands for protection from flood and droughts; stabilization of soil; provision of sediments and nutrients to support plant production and healthy soils; support of biodiversity; pollution control and detoxification; and the supply of resources for cultural, spiritual, aesthetic, and recreational activity (H. Berg 2002; Rudolf S. De Groot, Wilson, and Boumans 2002). Further, the identification in the region of wetlands identified and listed by the Ramsar Convention on Wetlands creates significant economic value which can be assessed through the measurement and subsequent valuation of the wetland ecosystem services (Brander, Florax, and Vermaat 2006; R. Turner, Georgiou, and Fisher 2008).

Traditionally, a theoretical basis for linking ecological diversity to human wellbeing has been lacking (Carpenter et al. 2006). As a result, one of the most significant challenges for the valuation of ecosystem services is the integration of ecological production models and economic valuation (Tallis and Polasky 2009a). Consequently, a priority identified by the Workshop participants is the development of models to estimate a baseline of ecosystem services based on existing biophysical and socio-economic conditions, necessitating the need for spatial analysis to address site-specific values for ecosystem service production (Nelson et al. 2009; Koch et al. 2009). An example of such a model is the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, which maps the spatial distribution of ecosystem services (Nelson et al. 2009; Tallis and Polasky 2009a; P. Kareiva et al. 2011).

Information about ecosystem services can be used to create incentives for ecosystem service provision and protection through pricing structures, incentives, policy, and profit-based private decision making (R. S. de Groot et al. 2010; Fisher, Turner, and Morling 2009).

Thematic Area 2: The Importance of Interdisciplinary Research

A recent editorial in *Nature* makes the seemingly anodyne, but nonetheless critically important claim that “[T]o solve the grand challenges facing society — energy, water, climate, food, health — scientists and social scientists must work together” (Editors of Nature 2015). Appeals for collaboration across the social and physical sciences to address problems of human sustainability are long-standing, broadly recognized, but extraordinarily difficult to implement given significant epistemological and methodological differences across the disciplines (Strang 2007). Interdisciplinarity entails “a process of answering a question, solving a problem or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline, and draws on the disciplines with the goal of integrating their insights to construct a more comprehensive understanding” (Repko, Newell, and Szostak 2011). Achieving integration of insight requires intensive collaboration across disciplines from the moment of conceptualization of a research problem, through collection of disparate datasets using quantitative and qualitative methodologies, to recognition of secular and cyclical patterns within datasets, and ultimately generation and testing of conceptual models that describe and simulate the dynamic interactions between humans and their environment.

Given the tremendous rate and scale of environmental and socio-economic changes occurring within the Mekong, and given the fact that these are occurring across a highly complex multi-country transboundary watershed, the complex adaptive systems of the coupled social-environmental Mekong system are intrinsically difficult to manage due to the dependencies, competitions, relationships, and other interactions between the different components of Mekong socio-economic systems and the Mekong environment (Olsson, Folke, and Berkes 2004). Such complex adaptive systems have distinct properties that arise from these relationships, including non-linearity (Scholes et al. 2013), emergent phenomena

(Olsson, Folke, and Berkes 2004), cross-scale interactions (Levin 1998) and adaptation and feedback loops (Price 2004), among others. Interactions between well understood social or environmental components can lead to unexpected outcomes when they are coupled into systems (Scholes et al. 2013). While the sustainability of water resources can depend on dynamic interactions among natural, social, and infrastructure systems, typical water resource planning and management approaches are based on methodologies that ignore feedbacks and adaptations among these systems (Giacomoni, Kanta, and Zechman 2013).

With respect to the Mekong social-ecological system, understanding future trajectories of natural resource and human sustainability in the region requires a holistic understanding of: (1) the integrated social and natural system beginning with physical changes in hydrology caused by human actions on the landscape and by climate change; (2) the effect of these changes on the provision of ecosystem services; (3) the short and long-term human response and adaptation strategies to the existing and changing patterns of the social-ecological system and; (4) subsequent feedbacks from those responses on the future provision of ecosystem services. In order to fully assess the effect of changes in land use and climate on water sustainability, it is necessary to understand how human populations use and affect the hydrological system (Philip Hirsch 2016; Chau et al. 2015; Nikula 2008), and to approach these understandings using a coupled social-ecological framework (Ostrom 2009).

To document and predict changes in ecosystem service provision in the Mekong region on centennial, decadal, and annual scales, and to evaluate how humans will adapt in the long term, we must understand not only the physical parameters of water, sediment and energy fluxes, but also the dynamic interaction of these parameters with human actors holding distinct "values, preferences, motivations, perceptions, rationales and decisions, from the individual to the collective (societal) level" (Barthel and Seidl 2017). This will require new methodological tools and theoretical frameworks that creatively integrate quantitative and qualitative social science research on human behavior, including household surveys, experimental techniques, and scenario-based simulations, with biophysical measurements of the Mekong basin's ever-changing environment.

Thematic Area 3: The Importance and Utility of Integrative Modeling

A consensus emerged at the workshop on the importance of integrated modeling as the most appropriate way to apply interdisciplinary research to a complex, dynamic, social-ecological system experiencing coupled human-environmental feedbacks and responses (B. L. Turner et al. 2003). However, coupled social-ecological modeling can involve particular difficulties, including the challenge of modeling the target system with the appropriate level of detail, choosing relevant variables and processes, choosing the appropriate level of aggregation (Eisinger and Thulke 2008), and comparing results with other models or studies (Schlüter et al. 2012). Nonetheless, progress has been made in the use of models which integrate human behavior and physical change (Johnston & Kummu, 2012)(Kainuma, M., Matsuoka, Y., & Morita 2011)**,** including for future trajectories for Mekong hydrology (Pokhrel et al. 2018a; Johnston and Kummu 2012a; Räsänen et al. 2012; Schilling et al. 2008; Orr et al. 2012; Manh et al. 2015), for fisheries (Ringler and Cai 2006; Ziv et al. 2012b; Ishikawa, Hori, and Kurokura 2017), land use change (Foran et al. 2013a; Schmitt, Rubin, and Kondolf 2017; Ornetsmüller, Verburg, and Heinimann 2016; Cassidy et al. 2013; Heinimann et al. 2007), hydropower development (Arias et al. 2012a, 2014; T. Piman, Lennaerts, and Southalack 2013; T. B. Wild and Loucks 2015)**,** and economic development (Foran et al. 2013a; Seto 2011; Garschagen et al. 2012; Christopher Sneddon and Fox 2012; Fischer-Kowalski and Haberl 2007).

Spatial analysis using Geographic Information Systems (GIS), and the integration of remotely sensed data, can provide not only a quantifiable framework to allow integration across social and physical science disciplines (Bockstael 1996; Guong et al. 2012; Dollar et al. 2007; Ahern 1999), but also across social-ecological systems, what may require measurement using vastly different observational units and/or different scales (Binford, Lee, and Townsend 2004; W. Wang et al. 2016; Goodchild 1996), such as for the integration of climate models with household survey data (J. S. Felkner and Townsend 2011)(Felkner et al. 2009). Remote sensing data, which can be integrated with social science data in GIS systems (Rindfuss and Stern 1998), provides unequaled potential for comprehensive data collection across space and time and provides invaluable inputs for coupled social-ecological science (Pettorelli, Safi, and Turner 2014; Kuenzer et al. 2013b).

Of particular utility is modeling to produce outcomes relevant for policy and decision-making, including the evaluation of historical and current decisions, predictive modeling for future scenarios, identification of sources and areas of risk, and human response to risk. Modeling of future scenarios is valuable for identifying sustainable trajectories and outcomes (Swart, Raskin, and Robinson 2004), for conservation policy (Peterson, Cumming, and Carpenter 2003), for integrating landscape ecology and landscape planning (Ahern 1999), and for quantifying large-scale or regional impacts of water infrastructure development, human alterations of the hydrologic system, or climate change on flooding, hydrologic, or habitat changes (T. Piman, Lennaerts, and Southalack 2013; Räsänen et al. 2012; Matti Kummu and Sarkkula 2008a; Arias et al. 2012b). For example, integrative models linking system hydrology, vegetation, and fish productivity in the Mekong have been developed (E. Baran and Myschowoda 2009; Ziv et al. 2012a; Dugan et al. 2010a; Junk and Wantzen 2004; Dirk Lamberts and Koponen 2008; Kite 2001; Gordon W. Holtgrieve et al. 2013a) (Sarkkula, Keskinen, Koponen, Kummu, Richey, Varis, et al. 2012) and subsequently, future impact scenarios can be developed based on different development and climate change scenarios (Phi Hoang et al. 2016a; Vastila et al. 2010). Similarly, future trajectories for hydropower, land use, and economic development and their impacts on Mekong hydrology (Lauri et al. 2012; Pokhrel et al. 2018a; Räsänen et al. 2012; T. D. Dang et al. 2016), biological productivity (Dirk Lamberts and Koponen 2008), water balance (Schilling et al. 2008), and fisheries (Sarkkula, Keskinen, Koponen, Kummu, Richey, and Varis 2012)(Dugan et al. 2010a; Orr et al. 2012) have been evaluated. Predictive and scenario-modeling approaches are potentially useful to bridge the gap between scientific research and communication to policy makers and the wider community, by exploring, for example, impacts of alternative policy implementations or regulatory frameworks (Chu Thai Hoanh, Suhardiman, and Anh 2014; Foran 2015b; R. M. Friend and Blake 2009; Glassman 2010; Smajgl et al. 2015a), quantifying impacts on food security or agricultural productivity (Cosslett and Cosslett 2014; Mainuddin, Kirby, and Hoanh 2011; Sabo et al. 2017; Ziv et al. 2012a; Sarkkula, Keskinen, Koponen, Kummu, Richey, and Varis 2012) or fisheries (Kite 2001; Dugan et al. 2010a), and related trade-offs. An additional benefit of predictive approaches is to help identify areas at risk, compare perceptions of risk against actual risk, and to gain an improved understanding of uncertainties and their causes (Dung et al. 2015; Thompson et al. 2013; Thompson et al. 2014; Kubiszewski et al. 2013; Lebel et al. 2009; Trung & Thanh 2013; Winsemius et al. 2016; Polack 2010; Ghadim et al. 2005).

InVEST, which uses GIS as a unifying framework, has been shown in a number of studies to aid in management of natural capital, provision of ecosystem services, and help to design policies for future resilience (Tallis and Polasky 2009; Redhead et al. 2016; Ting et al. 2014; Song et al. 2015; Sanchez-Canales et al. 2012; Isely et al. 2010). Other innovative approaches include the use of Agent Based Modeling (ABM) to create a framework that allows for the exploration of the feedback of human decisions on environmental dynamics and vice-versa. ABM has been used, for example, to integrate Mekong aquaculture farmers' production system choices and fisheries strategies, local knowledge, and poverty constraints with planning approaches used by decision makers to explore the sustainability of scenarios of future aquaculture and fisheries development (Joffre et al. 2015; Cabral et al. 2010). Structural economic modeling strategies, which can be combined with agent-based approaches, can explicitly model endogenous interactions between household agents' perceptions of risk and predict outcomes such as crop production as a function of that perception, to understand the impact of farmers' intended adaptations to climate change, or to assess the sustainability of rural water systems (John Felkner, Tazhibayeva, and Townsend 2009; J. S. Felkner and Townsend 2011; H. Le Dang et al. 2014; Dascher, Kang, and Hustvedt 2014; Masduqi et al. 2010; Ballantyne, Packer, and Falk 2011). Systems dynamics modeling can incorporate socioeconomic data and its linkages to biophysical changes in the context of land use change, allowing interrelations between distinct variables, such as household income and water provision, to be more dynamic rather than linear (Kim, 2012; Pittock, Dumaresq, and Bassi 2016; Chapman & Darby 2016; Winz et al. 2009; Sehlke & Jacobson 2005). Bayesian modeling can express relationships probabilistically and perform risk assessment, and has been used to model environmental factors driving fish production in the lower Mekong basin (Eric Baran and Baird 2003), Mekong fisheries management and aquatic resources management (Eric Baran and Baird 2003; Eric Baran et al. 2010; E Baran, Jantunen, and Chheng 2006), Mekong basin climate change (Huang et al. 2014), and policy analysis for the Tonle Sap (Varis and Keskinen 2006). Social science behavioral experimental methods have been used to understand household preferences in Vietnam (Tanaka, Camerer, and Nguyen 2010), collaborative water resource decision-making (Nyerges et al. 2006), and for promotion of water and energy conservation using a social-ecological framework (Kurz, Donaghue, and Walker 2005).

Research Thematic Area 4: The Importance of Scale

Since the Mekong is an interconnected network that is affected in significant ways by human activities, its functioning as a hydro-ecological system is differentially affected by both spatial and temporal scale-dependent societal processes (Dore, Lebel, and Ausaid 2010; Louis Lebel, Garden, and Imamura 2005; R Edward Grumbine 2018). Examples of cross-scale interactions in the Mekong include the impacts of larger scale (e.g. national or regional) policies on the collapse of local fisheries, or the effects of regional-scale drought on global food prices. Multi-scale assessments have been found to improve analyses of scale-dependent processes, improve analysis of cross-scale effects, provide better understanding of causality, and improve accuracy and reliability of findings (Scholes et al. 2013).

Climate change, hydropower development, and a host of related and impacted ecosystem services operate in particularly influential ways at the trans-boundary and regional levels (R Edward Grumbine and Xu 2011; T. Piman, Cochrane, and Arias 2016b; Eastham, Mpelasoka, Mainuddin, et al. 2008; Dugan et al. 2010b; Kuenzer et al. 2013a), while major processes like hydropower development and climate change operate and intersect on diverse timescales. Whereas the impacts of hydropower projects on Mekong hydrology (e.g., increased reservoir functioning, changes in average monthly water levels) are more immediate, the effects of climate change (e.g., increased annual precipitation, higher temperatures, sea level rise) will occur over the course of decades and longer (M. Keskinen et al. 2010).

Similarly, the economic valuation of ecosystem services is entirely scale-dependent in that the calculated values vary with the scale of human involvement with the riverine system (Loc et al. 2018). Such values may change, per spatial or temporal unit, in large rural areas compared to dense urban ones, with changes in land use that might provide optimal returns at varying scales, or with population expansion into forested areas that may change social-ecological feedback dynamics (R. Friend and Thinphanga 2018).

Scientific knowledge of the river system is spatially and temporally scale-dependent, because certain environmental processes occur at different scales and must be studied at those scales, and thus disciplinary-specific research may be focused at different scales (Louis Lebel, Garden, and Imamura 2005). This highlights the necessity of considering the scales at which scientific research has been or is currently being conducted, in relation to the scales at which it *should* be conducted to be representative of specific ecological or social systems, or of gaps in scientific knowledge (Käkönen and Hirsch 2009). Finally, policy development is directly related to questions of scale, especially since implementation is defined by jurisdictions of governance which operate at scales that are distinct from those of hydro-ecological processes, and because specific physical/environmental processes typically span governance boundaries and scales (Louis Lebel, Garden, and Imamura 2005; Dore, Lebel, and Ausaid 2010).

KEY RESEARCH AREAS

Thematic Area 5: The Impact of Hydropower and Climate Change

As of 2019, more than 3235 MW of hydropower facilities have been built over the last 10 years in the lower Mekong, while projects under construction will represent an additional 3209 MW, with an additional 134 projects planned (International Rivers 2019). The development of hydropower is an attractive economic option for the Mekong countries. Given current development trends in the region, power demands are expected to rise seven percent per year between 2010 and 2030, yielding a substantial and highly lucrative energy market (Dore, J Xiaogang, Y Yuk-shing, 2007; Mekong River Commission, 2018).

Recent research has documented and estimated the potential impact that these extensive hydropower projects could have on Mekong hydrology (Hecht et al. 2019; Pokhrel et al. 2018b), biodiversity (Ziv et al. 2012a), natural fisheries, and geomorphology (G. Mathias Kondolf et al. 2018), with consequent negative impacts on Mekong food security, traditional livelihoods, and revenue losses across multiple economic sectors for millions of Mekong inhabitants. For example, ecosystem service valuations have shown that revenue losses in fisheries alone, with up to 50 percent losses of native stocks, could far outweigh hydropower economic gains through the loss of fish habitat, biodiversity, and subsequent catch levels (Intralawan et al. 2018b).

Existing hydropower projects have affected measured impacts on hydrological alteration indicators such as increased water level fluctuations and decreased flood extent (Sabo et al. 2017)(Cochrane, Arias, and Piman 2014; Lu et al. 2014). Impacts from the most recent wave of hydropower development in the Lancang area have considerably modified river discharges and have caused a marked increase in dry season water levels as far as Central Cambodia in Kratie, including a 41-74% increase during March-May 2014. Other studies have suggested additional impacts of dams on fish migration connectivity, aquatic primary production, habitat suitability, and nutrition value (Arias, Cochrane, and Elliott 2014; Intralawan et al. 2018b; Ziv et al. 2012a; Arias et al. 2014).

However, the most drastic physical changes from hydropower will not necessarily be river flow alterations, but the reduction of the vast majority of the Mekong's river sediment trapped in reservoirs, leading to loss of lowlands in the floodplains and delta (Arias et al. 2014; G. M. Kondolf, Rubin, and Minear 2014; T. Wild and Loucks 2014) with potentially enormous impacts on food security and livelihoods for millions of inhabitants in Cambodia and Vietnam (G. Mathias Kondolf et al. 2018; Thanapon Piman and Shrestha 2017). Potential sediment and fisheries losses could be partially or largely offset through strategic spatial dam planning and placement, (Ziv et al. 2012a) or alternative dam operations that can allow sediment passage (Schmitt et al. 2018; T. Wild and Loucks 2014).

Increasing climate variability has also been driving environmental change in the Mekong in past decades, and this is expected to continue to accelerate during the next century (Lauri et al. 2012). Moreover, water level records indicate an increase in the magnitude of extreme events (anomalies) since the 1920s (Sabo et al. 2017). Regarding future climate change, recent research indicates that extreme flood events will continue to increase in both magnitude and frequency (Phi Hoang et al. 2016b).

Despite the improved quantification of these important dynamics, key unanswered scientific questions remain, as do related research needs. Current research does not provide sufficient understanding of the relative variation in impacts on different economic sectors, such as aquaculture and transportation. To address these and other important questions related to hydropower and climate change impacts, robust multi-sectoral monitoring and forecasting systems need to be improved for the region.

Thematic Area 6: The Future of Mekong Aquatic Ecology and Fisheries

Mekong aquatic resources are threatened by a variety of intrinsic and extrinsic factors (Dudgeon et al. 2006), including climate change (Arias et al. 2012b), hydropower development (Ziv et al. 2012a; P. M. Kareiva 2012), agro-industry (Xing 2013) , pollution (M. Berg et al. 2001), increasing fishing pressure (Kang et al. 2009), limited governance and management capacity (R.E. Grumbine 2017), a changing regional demographic (H. Li, Wei, and Korinek 2018), and new socioeconomic priorities (Morton and Olson 2018). Loss of inland fisheries could undermine food security for the region because often there is no feasible alternative for food, income, and livelihoods (Jamie Pittock, Dumaresq, and Orr 2017).

For more than a century, large-scale fishing on the Tonle Sap Lake was regulated through the use of commercial leasehold fishing lot concessions that covered most of the Tonle Sap floodplain, and which prevented access to prime fishing by the rural poor but centralized control of fishing among a small number of individuals (Arias et al. 2019). However, these concessions were abolished in 2012 allowing relatively unregulated fishing that has negatively impacted fisheries monitoring, leading to negative implications for the fishery (Jones and Sok 2015; Cooperman et al. 2012), including a decline in larger-bodied higher tropic riverine species and mean fish weight (Ngor, McCann, et al. 2018). In particular, without leaseholder protection, much of the flooded forest is being harvested (Dina and Sato 2015). Important changes to demographic and socio-economic priorities in the region (Smajgl and Ward 2017), are also driving fisheries harvesting further away from traditional fishing practices and towards more productive industrial techniques (Kc et al. 2017), increasing fishing pressure and making accurate scientific modeling even more challenging.

Recent studies have increased understanding of key interactions between the dynamic flood pulse that drives the Mekong system and aquatic biological production (E Baran and Jantunen 2005; Sabo et al. 2017), improved knowledge of regional hydrology (T. Piman, Cochrane, and Arias 2016a), climate change (Arias et al. 2014), hydropower impacts (Sabo et al. 2017), agricultural trade-offs (Cochrane et al. 2016), aquaculture impact (Anh et al. 2010), increasing fishing pressure (Ngor, McCann, et al. 2018), nutrient transport and availability(Matti Kummu and Sarkkula 2008c; Sarkkula, Keskinen, Koponen, Kummu, Richey, and Varis 2012), and modeling of interactions (Mekong River Commission 2018b). Studies have also helped address some critical gaps in ecological knowledge, including primary production (Gordon W. Holtgrieve et al. 2013b), fish species distribution (Kong et al. 2017), life-history traits (V.L Elliott, Chheng, and Uy 2017), population structure (Hurwood, Adamson, and Mather 2008), and food web ecology (Pool et al. 2017).

However, despite these recent knowledge advances, there are still important scientific questions that remain unanswered (Evers and Pathirana 2018; Phi Hoang et al. 2016b). Increased research is needed in these areas in order to accurately predict the impacts that hydropower (Golden et al. 2019) and floodplain loss from agriculture and irrigation schemes (Intralawan et al. 2019) will have on both ecosystem dynamics and the aquatic resources (Thanapon Piman and Shrestha 2017; Sabo et al. 2017). Further, to identify potential tipping points in the hydrological scheme, a more nuanced understanding of the relationship between hydrology and fish communities (Baumgartner et al. 2019; E Baran, Guerin, and Nasielski 2015), and the changes that climate and development will have on sediment and nutrient transport (Duc et al. 2018; Chen et al. 2019), is needed.

Additional research on the impact of loss of fertile soils (Fredén 2011), soil characterization (Takemura, Watabe, and Tanaka 2007), reservoir sedimentation (M. Kummu et al. 2010), and impacts of toxic substances including heavy metals and pesticides (H. Berg 2002; H. Berg and Tam 2018) on aquatic ecosystems and habitats is extremely limited despite their likely influence (Gu et al. 2017). Particularly in a fishery that is so biodiverse and indiscriminant (Mccann et al. 2015; Ngor, Legendre, et al. 2018), characterizing effective management will require an improved understanding of habitat requirements of the fish community (Hicks et al. 2017), food web dynamics (Pauly and Weingartner 1998), and interactions between production and habitat availability (Pettit et al. 2017). Currently there is insufficient knowledge about basic ecology, such as life-history timings (Baumgartner et al. 2019), reproduction, fecundity, effective population size, species distribution and abundance (Chea et al. 2017), movement of individuals and communities (Vittoria L. Elliott et al. 2019; Poulsen et al. 2004; Baumgartner et al. 2019), and population structure and dynamics (Tonkin et al. 2017), to determine fisheries' parameters used to manage fish resources elsewhere in the world (FAO 2003). Maintaining a continuous time-series of the fishery from long-term monitoring, supplemented with targeted studies, is therefore essential for creating accurate predictions of the impact of fishing pressure (White 2018) and future hydrological scenarios on resources.

Thematic Area 7: The Importance of Land-Use Land-Cover Change (LULCC)

Changing LULCC affects major changes in hydrological regimes in very small to very large drainage basins (DeFries and Eshleman 2004) as well as changes in basin-scale sediment production, transport, and deposition (J. J. Wang, Lu, and Kummu 2011), and manifold changes in ecosystem processes and services (Lawler et al. 2014). In the shorter term – a 30-year time horizon – LULCC in the Mekong will probably have a greater effect on the hydrological regime and ecosystem services of the Mekong River flood pulse than will climate change (McCluney et al. 2014).

Recent large-scale clearance of forests in the Mekong floodplain are transforming the floodplain landscape at an unprecedented rate (Arias et al. 2019): recent deforestation rates in areas surrounding the Tonle Sap watershed are among the highest on the planet, estimated at 0.9-1.7% annually (Hansen et al. 2013). These forest and wetland losses jeopardize the Tonle Sap fishery and bird populations, which use the floodplain forests as habitats and food resources derived from surrounding vegetation, and reduce ecosystem services including water purification and food for local populations (Arias, Cochrane, and Elliott 2014; G W Holtgrieve et al. 2013; Campbell et al. 2006b).

However, there are only minimal studies of past LULCC in the Mekong basin, but all to our knowledge focused on sub-regions within the basin (Cassidy et al. 2010, 2013)(Gaughan, Binford, and Southworth 2009)(Shrestha et al. 2018)(J. Fox et al. 2012)(Minderhoud et al. 2018; Lam-Dao et al. 2011; Tran, Tran, and Kervyn 2015; Markert et al. 2018; Lauri et al. 2012; Mohammed et al. 2018; J. Felkner 2000) and none at the full basin scale. These studies show that most important LULCC patterns in the Mekong basin have been significant loss of native forests, increase of upland crops, increase in tree crops (rubber, teak), and a loss of mangrove wetlands as they are replaced by aquaculture.

Each of these changes influences hydrologically based ecosystem services. For example, increases in upland tree plantations increase evapotranspiration, reducing runoff and subsequent streamflow, while increases in cultivated agriculture whether upland crops or rice fields has the opposite effect (Shrestha et al. 2016) (Markert et al. 2018). Urbanization also increases impervious areas, resulting in higher river discharge but with shorter and more intense flood peaks following individual rainstorms.

Increased hydropower development upstream will decrease the amplitude of the flood pulse, converting annually flooded land to permanently dry land. Given the recent history of LULCC in Cambodia, Thailand, Laos, and Vietnam, new land uses, most likely rice fields or tree plantations, industrial development and urbanization, can then be implemented on the flat, dry land comprised of fertile alluvial sediments near water (Cassidy et al. 2010, 2013; J. Fox et al. 2012; Shrestha et al. 2018). In these cases additional resources such as fertilizer and pumping water from the river or lake might have to be applied because the ecosystem services of an annual input of nutrient-rich sediments and water will no longer occur (Shamrukh, Corapcioglu, and Hassona 2001)(Sparks 1999). If industrial development or urbanization occurs, then infrastructure for storm-water disposal and flood control will become more important for regulating the hydrological regime.

LULCC in the Vietnamese Mekong Delta also has particular and important impacts: land subsidence is less pronounced where natural vegetation exists, but occurs more in areas dominated by agriculture, and most in urbanized areas (Minderhoud et al. 2018). The development of large-scale aquaculture, largely shrimp farms, has led to loss of about 50 percent of the Delta's mangrove wetlands and increased bank erosion (Lam-Dao et al. 2011). Decreases in the annual Mekong flood pulse along with sea-level rise will increase the salinity of Delta water (Smajgl and Ward 2015a), which may lead to even more area converted to salt-water shrimp farms, resulting in the loss of more of the ecosystem services provided by coastal mangrove wetlands.

It is clear that a comprehensive analysis of LULCC in the entire Mekong basin, coupled with models that link land cover with hydrological processes, sediment production and transport, and other ecosystem services, will require several specific research efforts. The main foci of research would be two-fold: to describe and explain the actual land-use and land-cover changes for the entire Mekong at a fine spatial scale over the past 40 years and to use this new understanding of LULCC to generate predictive models of future change. Recent advances in Ecological Forecasting (Dietze et al. 2018; Dietze 2017), makes the Mekong an excellent case study for both increasing our fundamental understanding of the influence of LULCC on hydrological ecosystem services in Southeast Asia as well as providing a link with basin management. Significant investment in up-to-date land cover datasets derived from satellite remote sensing and on-the-ground validation must be completed.

Thematic Area 8: Research on Mekong Trans-Boundary Governance

The Mekong flows through six countries—China, Cambodia, Laos, Myanmar, Thailand, and Vietnam—and therefore faces serious challenges in trans-boundary hydrological dynamics, ecosystem functioning, and governance and regulation. Crucial areas for continuing research consist of: (1) understanding what is actually being modified in the Mekong water system; (2) identifying institutions and governance arrangements that can jointly assess acceptable levels of modification and impediments to achieving those levels; and (3) evaluating the impacts of trans-boundary water utilization on sustainability and equitability in the Mekong region.

Major ecosystems and riparian functions are directly impacted and potentially determined by the nature and extent of trans-boundary cooperation. Examples include: the impacts of upstream hydropower development on downstream fish migration, biodiversity, and productivity (Dugan et al. 2010a; Villamayor-Tomas et al. 2016; Ziv et al. 2012a); the effects of economic development on Mekong sediment flows and budgets, and the resulting implications for downstream floodplain ecologies, food security, and livelihoods (G. M. Kondolf, Rubin, and Minear 2014; G. Mathias Kondolf et al. 2018; Räsänen et al. 2017); and alterations of hydrological regimes, including the Tonle Sap flood-pulse system, as a result of the construction of main-stem and tributary dams (Cochrane et al., 2014; Long Phi Hoang et al., 2018). Additional research is necessary to determine the nature, extent, and implications of multi-scalar changes along the Mekong River system as well as to elucidate the trans-boundary dimensions of the Mekong Food-Energy-Water (FEW) nexus (Marko Keskinen et al. 2016a, 2015; Smajgl and Ward 2013a).

Ecosystem services provide one viable research lens for assessing trans-boundary modifications (Bennett et al. 2015). Approaches that center on multi-scalar and cross-sectoral processes, such as Food-Energy-Water (FEW) and integrated water resources management (IWRM) frameworks, provide strategies for addressing Mekong social-ecological processes as trans-boundary, geopolitical challenges (Philip Hirsch 2016; Marko Keskinen et al. 2015; Smajgl et al. 2015a).

Research is essential for examining how trans-boundary hydropower development is appraised and the role of public involvement and multiple stakeholders in that process (Dore, Lebel, and Molle 2012; Hensengerth 2009; L Lebel, Garden, and Imamura 2005; Mirumachi and Torriti 2012; Chris

Sneddon and Fox 2007a). Similarly, more knowledge is needed to assess the degree to which international legal and environmental standards are maintained in the execution of both private and public hydropower projects (Bearden 2010; Boer et al. 2016). The controversial Xayaburi Dam in Laos presents a case in point in which the 1995 Mekong Agreement and other international laws were violated, thereby revealing the difficulties as well as the necessity of developing consultation processes for equitable, trans-boundary decision-making and enforcement (Hensengerth 2015; Rieu-Clarke 2015). Sustainability endeavors by Mekong national governments and development agencies are conceptually framed by the Integrated Water Resource Management (IWRM) framework, adaptive management and more recently, the water food and energy nexus architectures (R. Edward Grumbine, Dore, and Xu 2012; Louis Lebel et al. 2006; Foran 2015b; Smajgl et al. 2015a).

However, the MRC has been criticized for having flawed methods for generating, disseminating, and archiving scientific research and findings (Campbell 2007a; Suhardiman, Giordano, and Molle 2015), in particular for failing to share research for widespread use by governments, the private sector, and civil society organizations (Dore and Lebel 2010; P Hirsch et al. 2006; Käkönen and Hirsch 2012; Plengsaeng, Wehn, and van der Zaag 2014). The 1995 MRC agreement specifies the need for accurate, real-time sharing and exchange of data and information (Mekong River Commission, 1995). However, despite the agreements and a long history of data collection in the basin, data and information sharing is limited or has frequently failed to fulfill agreed upon legal obligations (Affeltranger and Frederic 2009; Gerlak, Lautze, and Giordano 2011; Plengsaeng, Wehn, and van der Zaag 2014). Gerlak, Lautze and Giordano (2011) and Plengsaeng, Wehn and van der Zaag (2014) contend that the delayed implementation of data-sharing procedures in relation to institutional and legal obligations is due to non-technical obstacles, not simply the lack of data or technical issues, including: a lack of understanding of Procedures for Data and Information Exchange and Sharing (PDIES); unclear classification of data and information with respect to national security; concerns about losing control over shared data; and the absence of moral and institutional pressures to share. Improved understanding of the diverse motivations and attitudinal constraints of decision makers in all Mekong countries (including Myanmar and China) were identified as key for developing a common culture of meaningful data exchange.

Thematic Area 9: The Importance of Assessment of Mekong Low-Income Resilience

Although rapid urbanization is occurring in Mekong countries, more than 85 percent of the basin's population lives in rural areas. The livelihoods and food security of most of the rural population is highly dependent on the river system and its ecosystem services, with over 60 percent of the population engaged in water-related occupations that are vulnerable to shocks and degradation (Syaukat 2012). Most of these inhabitants are rural farmers/fishers, and more than 35 percent of the populations of Cambodia and Lao People's Democratic Republic have incomes below the poverty line and often lack access to basic government services (Syaukat 2012; C. A. Fox and Sneddon 2019). About half of all villages are inaccessible by all-weather roads, food security and malnutrition pose great challenges, and throughout the Lower Basin, inequalities are generally increasing between urban and rural groups (Mekong River Commission, 2018).

These rural populations along the Mekong are crucially dependent on ecosystem services that are generated by the seasonal aspects of the Mekong River flow, as well as on primary ecosystems which are being altered by human actions, particularly the construction of dams (Yermoli 2009; Long P. Hoang et al. 2019; T. D. Dang et al. 2018; X. Li et al. 2017; Hecht et al. 2019). These include furnishing fish protein (Barlow et al. 2008; E. Baran and Myschowoda 2009; Orr et al. 2012; Ziv et al. 2012a; Dugan et al. 2010a), depositing nutrient rich sediment essential to local rice farming techniques (A. D. Chapman et al. 2016; Manh et al. 2015) and gallery forests which provide a variety of essential livelihood inputs (Arias et al. 2013).

However, shifts in ecosystem service provision currently occurring in the Mekong as a result of hydropower and land use changes will require local adaptation of new agricultural practices and technologies, forcing changes to traditional rice-fish farming practices (Dugan et al. 2010a; Orr et al. 2012; Moder et al. 2012; Coclanis and Stewart 2011; Sharma et al. 2016). For example, the Mekong flood pulse is an essential source of the potassium budget for traditional agriculture, and alterations in the flood pulse extent will require replacement, most likely with chemical fertilizers, but such alterations could be costly and alter household choices for agricultural production and consumption (Hoa et al. 2006). In other cases, this may lead to abandonment of land and encourage migration (Heinonen 2006).

Consequently, there is a need for the development of models that can improve understanding of factors that will improve low-income rural resilience to these dynamic socio-environmental changes (Kura et al. 2017; A. Chapman and Darby 2016; H. Le Dang et al. 2014; Perez-Felkner et al. 2020). Such models will need to specifically incorporate socioeconomic variables of risk avoidance (Swierczek and Ha 2003), food security (Mainuddin, Kirby, and Hoanh 2011; Ziv et al. 2012a), and financial income and livelihoods (Arouri, Nguyen, and Youssef 2015; Kien 2011; Turunen et al. 2010).

Responses and strategy changes are in part a function of cultural values and traditions that can only be assessed through social science assessment tools, and ethnographic studies are an essential tool in this process (Lambin and Meyfroidt 2010). For example, (Kura et al. 2017) found widely variable household resilience to displacement by hydropower within a single village in Laos, while (Sumner, Christie, and Boulakia 2017) showed how traditional gender roles directly impacted the effectiveness of conservation agriculture systems introduced to smallholder farmers in Battambang Province, Cambodia.

In addition to improving understanding of the social-ecological dynamics of rural low-income resilience, alternative policy implementations and potential regulatory frameworks to facilitate this resilience need to be explored and modeled (Johnston and Kummu 2012a). For example, (Clements et al. 2014) found that the creation of Protected Areas (PAs) in Cambodia appears to increase income security for households that depend on the forest and land resources for their livelihoods by ensuring improved access.

Thematic Area 10: Additional Considerations Pertaining to Mekong Scientific Data

A clear consensus in the workshop was that there is an urgent need in the Mekong for expanded long-term and short-term datasets quantifying biological resource dynamics and their environmental drivers, including data related to Mekong river dynamics, floodplain ecosystems, fisheries, and LULCC including deforestation. Existing long-term Mekong ecological datasets are desperately sparse: the longest continuous record of a biologic resource to date in the Mekong is the seasonal Tonle Sap River stationary trawl fishery monitoring program initiated in 1994 (Halls et al. 2013; Sabo et al. 2017).

However, advances in remote sensing data acquisition and distribution, including advances in sensor technology and increases in the spatial and temporal resolution of remote sensing data that can be used for continuous monitoring of environmental conditions, populations, and LULCC offer an immediate potential source for data that can be used for real-time forecasting and resource management (Arias et al. 2019). An example of such an effort is the launching of the "SERVIR-Mekong" project by NASA and USAID, in collaboration with 90 nations in the Group on Earth Observation, to strengthen regional environmental monitoring in the five Lower Mekong countries by freely sharing a continuous stream of NASA remotely-sensed climate, weather and other Earth observation data for improved water management, land use planning, natural resource management, and food security (Mohammed et al. 2018). SERVIR provided products have been used in the Mekong for drought and crop forecasting

(Abhishek et al. 2018), measuring dam impact on sediment retention (Munroe et al. 2017), hydrological decision-making (Mohammed et al. 2018), and land cover monitoring (Saah et al. 2016).

Governments in the region are improving the support of longer-term socioeconomic datasets, such as the Cambodian Socio-Economic Surveys (CSES) which have collected extensive household-level data on demographics, income, livelihoods, and agriculture since 1999 (Fujii 2008).

However, there remains an urgent need for continuing advances in economic, social science and biophysical data collection methodologies and analytical tools to support Mekong water sustainability research, articulated as social-ecological systems. These data should be capable of: addressing the dynamic interactions and sector interdependence in an increasingly connected Mekong region; increasing the utilization of GIS and remote sensing as a facilitating framework to merge quantitative and qualitative data; and coherent and comprehensive social and economic data enabling trans-disciplinary research. Also important are identifying and assessing key data lacunae that are relevant to the Mekong sustainability-adaptive governance framework: workshop discussions specified fishery distribution, composition and migration, nutrient and sediment loads, and distribution. Also needed are processes to address data lacunae through more organized, searchable data integration and access: discussion focused on collating standardized data at compatible resolutions, and relying on international metadata processes to assess data validity and reliability.

Data is the starting point to enable discovery of sustainable solutions for the Mekong, providing information (who, what, when and where), leading to knowledge (how to manage), improving understanding (clarity on cause and effect), resulting in wisdom (the ability to perceive and evaluate the long-run consequences of actions and behavior). In the absence of data, it is difficult to review assumptions, methods, analytical treatments, and attendant policies to help understand why differences between sustainability outcomes and predictions occur.

PRACTICAL FOCI MOVING FORWARD

Thematic Area 11: The Importance of Stakeholder Engagement and Participatory Planning

Water resource systems are characterized by a complex web of diverse uses that may cut across social, economic, administrative, and political units encompassing a large number of differing stakeholders - individuals, communities, commercial bodies, and government departments at local, regional and national levels. These stakeholders possess different agendas and sets of interests (Grimble and Wellard 1997) that may result in complementary or competing use of resources (Sultana and Thompson 2004).

In the Mekong, stakeholder participation is crucial for consideration of options and trade-offs for on-going and future Mekong water resources development (Smajgl and Ward 2015a). This is particularly true in the trade-off between economic and energy development (including hydropower) and food security (including fisheries and agriculture) (Dugan et al. 2010b; Orr et al. 2012; J Pittock et al. 2015; Kubiszewski et al. 2013), but also for responses to climate change (Droogers and Aerts 2005) and disaster risk mitigation. Inputs of all levels of stakeholders are important for long-term water sustainability, especially when transboundary decisions impact water supply, food security, and other critical social goods and services that are difficult to replace (Eric Baran and Jantunen 2004; Huntjens, Lebel, and Furze 2015; R. Edward Grumbine, Dore, and Xu 2012). Stakeholder engagement can enable higher quality policy and management decision-making with more complete information that can improve the selection, efficiency, effectiveness and evaluation of policies and projects (Dougill et al. 2006; Huntjens, Lebel, and Furze 2017), anticipate and ameliorate unexpected negative outcomes (Fischer 2000; Koontz and Thomas 2006; Beierle 2000; Kastens and Newig 2008), and transform adversarial relationships (Stringer et al. 2006). Further, stakeholder engagement can empower disadvantaged groups and local communities

(Leeuwis et al. 2002; Trung et al. 2004; Sultana and Abeyasekera 2008). (Garnett et al. 2009) highlight the importance of involving stakeholders in the shaping of research questions from the outset, while participation may make research more robust by providing higher quality information inputs (Stringer et al. 2006; Reed 2008) and understanding of human dynamics within the system (C.T. Hoanh et al. 2003). Scenario building is a participatory process that involves multiple stakeholders and their creative visions for assessing situations in which future-shaping factors are uncertain and often impossible to control (Swart, Raskin, and Robinson 2004; Evans et al. 2006; Biggs et al. 2018). Stakeholder engagement also enables knowledge exchange/transfer between researchers and non-research audiences, a specific mechanism for disseminating research findings and facilitating the translation of research findings into action (Phillipson et al. 2012; Keown, Van Eerd, and Irvin 2008).

As a transboundary basin, the Mekong suffers from a lack of existing effective forums for decision-making utilizing stakeholder inputs, as seen, for example, in the lack of assessment and public consultation in hydropower development. In its Strategic Plan 2006-2010, the MRC adopted stakeholder participation as essential for an integrated approach on water resources management (MRC, 2009).

Thematic Area 12: Bridging the Gaps Between Scientific Research and The Domain of Policy Making; Improving Effective Communication and Engagement From the Research Community to Policy Makers

Despite the value of integrating research and policymaking to promote sustainability in the Mekong region, research findings are not always operationalized in government-based decision-making. This disconnect between science and policy derives in part from a dearth of effective institutions for sharing research and from competing political interests which limit the dissemination of scientific results (Thu and Wehn 2016; Plengsaeng, Wehn, and Van Der Zaag 2014; Chenoweth, Malano, and Bird 2001; Chris Sneddon and Fox 2007b; Philip Hirsch et al. 2006).

Ensuring the accessibility and communication of scientific research to policymakers is crucial for identifying the best options for securing water sustainability (R. Edward Grumbine, Dore, and Xu 2012; Jacobs et al. 2016; Pahl-Wostl, Palmer, and Richards 2013), supporting livelihoods (Biggs et al. 2015), and protecting ecosystem services (ES) and food-energy-water (FEW) security (Marko Keskinen et al. 2016b; Scanlon et al. 2017; Foran 2015a; Jamie Pittock, Dumaresq, and Bassi 2016) across the Mekong. Similarly, scientific data and results can be used to create and improve environmental regulations and standards that encourage accountable investments in Mekong development (Molle, Foran, and Käkönen 2009; Marko Keskinen et al. 2016b). This entails efforts to improve science-policy exchanges and participatory frameworks within the context of trans-boundary power asymmetries and multi-level governance systems (Smajgl et al. 2015b; Bhagabati et al. 2014; Huitema et al. 2009; Armitage et al. 2015). Additionally, emphasis needs to be placed on translating technical information and probabilistic modeling into accessible forms of knowledge that can adapted to policymaking (Smajgl and Ward 2013b).

There are several possible solutions for addressing the barriers between science and policy. Ecosystem service valuation offers opportunities to operationalize scientific findings in the economic assessment of natural capital (Guerry et al. 2015), and has been advanced by the WWF and Mekong policymakers to improve government valuations of resources (WWF 2013). The use of Geographic Information Systems (GIS) and GIS-based software can enable scientists to capture past, present, and future processes and changes in the Mekong system in ways that are understandable across diverse disciplines and audiences (Takamatsu et al. 2014; Matti Kummu and Sarkkula 2008b; Johnston and Kummu 2012b).

Secondly, developments in participatory processes (e.g. scientific workshops, community-led stakeholder meetings) linking researchers, stakeholders, and policymakers will provide important opportunities for communicating scientific knowledge and informing resource management and policy (Hassenforder, Smajgl, and Ward 2015; Foran et al. 2013b; Smajgl and Ward 2015b; Campbell 2007b). Similarly, there is a need to increase the number of Mekong-based peer-reviewed scientific journals in order to facilitate information exchange and provide additional forums for scientific communication in the region.

Finally, scientific organizations can implement projects directed at building institutional capacities across academic communities, NGOs, and government sectors. For example, Fauna and Flora International (FFI) has collaborated with the Centre for Biodiversity Conservation at the Royal University of Phnom Penh (RUPP) to direct a capacity-building program that promotes postgraduate education, conservation research, and dissemination of scientific findings (Souter 2014).

DISCUSSION

The 12 thematic issues treated here identify a comprehensive agenda for the science of Mekong River water sustainability moving forward. This agenda is crucial to the tenuous sustainability of one of the world's great river basins, an indispensable repository of ecological and biodiversity richness, and a region where millions of inhabitants depend directly on the ecosystem services provided by the water system, but which is currently experiencing dramatic change and potential threats to long-term sustainability. These 12 themes emerged through a rigorous series of discussions and engaged group exercises among an interdisciplinary group of physical and social scientists with extensive Mekong expertise. Because the participating scientists represented a range of physical and social sciences relevant to the identification of a Mekong scientific sustainability agenda, we believe that this agenda has been identified objectively.

The importance of interdisciplinary collaboration and integration, particularly across the social and physical sciences, emerged strongly across all themes. A strong consensus emerged that Mekong water sustainability cannot be understood or managed without equal understanding of its environmental and social systems, their interactions and feedbacks at multiple scales, and that science needs to inform policy and governance. Mekong social-ecological processes occur across multiple spatial and temporal scales, the interactions across scales are fundamental in determining the dynamics of the system at any particular scale, and interactions between well understood system components can lead to unexpected outcomes when they are coupled into systems, due in some cases to non-linear or emergent feedbacks. Consensus also emerged on the importance of integrative modeling as a powerful tool to understand multi- and cross-scalar coupled social-environmental dynamics, to use that understanding to model predictions under alternative scenarios, and then use those to inform management and governance approaches.

The objective of sustainable water management is to negotiate and implement a science-based and socially acceptable level of surface and ground water system modification. Consensus on the science of sustainable water management coheres around a problem-driven understanding of the dynamics of coupled social-ecological systems. Mediating contested water values foregrounds the design and implementation of institutions and governance to coordinate conflicts between an expanding, often non-commensurate array of water related facts, values, social norms, rituals, icons, and narrative. Enduring solutions also require community knowledge coupled with institutional analysis and an understanding of the roles of different systems of governance.

Further, discovering Mekong sustainability is a social-political debate. Although it can be articulated in the language of science, the solutions reflect questions of social choice, importance and preference, rather than solely technical expertise and merit. The failure of technical studies to assist in the resolution of sustainability controversies is part of a larger pattern of failures of discourse in problems that put major societal values at stake. Grumbine, Dore and Xu (2012) and Ward (2013) argue that the discussion of sustainability goals and visions of the future remain inhibited in the Mekong. Under these conditions, planning and management approaches that fail to embrace the social and value-based dimensions of Mekong sustainability as well as technical/biophysical dimensions, will be limited in the ability to foster resolution. Such failures may exaggerate disagreement rather than contribute to the resolution of a socially agreed level of Mekong system modification.

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