PROJECT DESCRIPTION

1. CONCEPTUAL FRAMEWORK AND PROJECT AIMS

The Sustainable Mekong Livelihoods Project (SMLP) aims to help sustain the socioecological Food-Energy-Water Systems (FEWS) in the lower Mekong River Basin (MRB). To realize this ambitious goal, we propose a conceptual framework that links current and future hydropower production and climate to flood-pulse hydrology, food security, nutrition, resource users, governance, and development (Fig. 1). ***Common Disciplinary Thread***: *Flood-pulse hydrology drives food security in the MRB, but hydropower development and climate change are threatening the connection between the flood-pulse and sustainable livelihoods.*

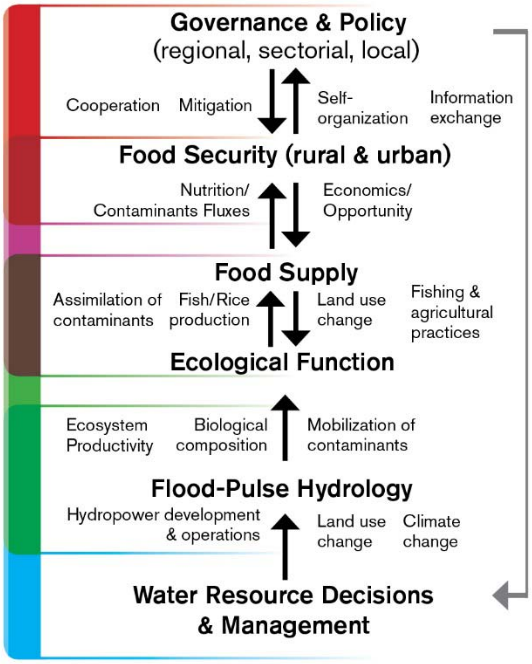


Fig. 1. **Conceptual framework** describing links among research elements.

Climate change will alter rainfall amounts and may alter the timing of the South Asian Summer Monsoon (SASM)[1,2] and ensuing floods. There is much less certainty about the joint effects of climate change and hydropower operations on flood-pulse timing and the magnitude of impacts on ecosystems and livelihoods. This flood-pulse stimulates primary and secondary production and cues the reproductive migration of fish species, the dominant source of animal protein for over 60M people in the lower MRB.[3,4]Summer rains also sustain rice production; Viet Nam and Thailand are the world's 2nd and 3rd top rice exporters, and all lower MRB countries aim to be net rice exporters.[3] Flood-pulse strength, timing and duration will evolve due to dam construction and climate change, but the impacts on the food system are largely unknown.

Our proposed work will:

- Offer a quantitative framework for predicting the effects of climate change, hydropower development, and subsequent operations on rice/fishery yields and fish biodiversity;
- Produce the first quantitative estimates of nutrient and contaminant fluxes from rice and fish to the people who depend on river and floodplain fisheries for nutrition and their livelihoods;
- Pioneer a modeling framework integrating hydrologic models and hydropower operations to deliver the flood-pulse, improve food security, and manage tradeoffs between power generation, and nutrient and contaminant fluxes to people;
- Develop a quantitative bargaining modeling tool for understanding the conflicts between different biophysical scenarios and how cooperation might emerge to improve access to food and livelihoods

The specific aims of our proposed research are to:

- Estimate the impact that climate change, land-use, and hydropower production have on the flood-pulse and its subsequent effects on food security, primarily determined by the production and quality of freshwater fish and rice;
- Quantify nutrient composition and contaminant loads in fish and rice from a critical growing region—the Tonle Sap Lake—through nutrient/contaminant profiling and evaluating change under different hydroclimate-hydropower operations scenarios;
- Model the governance, cooperation, and net welfare of populations at regional, country, and local scales using game-theoretic and robust decision-making approaches;

- Estimate integrated resiliency measures for the MRB FEWS to adverse climate, political, and economic scenarios and formulate risk mitigation recommendations (i.e., coordinated dam operations); and
- Collaborate/communicate with stakeholders to maximize research relevance and disseminate results through an innovative STEM training program in sustainability.

2. RESPONSE TO PREVIOUS REVIEWS

This proposal was reviewed favorably and deemed competitive for funding last year. The panel concluded that it was very well thought out and could become excellent with a more comprehensive socioeconomic component and system integration metrics, and a better context for food security within the FEW nexus. This year we have addressed concerns regarding integrated metrics and socioeconomic analysis by coupling game theory and outputs from hydrologic and food production functions within a water resources optimization model that considers coordinated dam operations and the effects of actors and their choices on the optimal allocation of water to hydropower and food production (fish and rice). Hence, optimization can be compared with the influence of the social part of this socio-ecological system. We develop metrics of system integration and resiliency in the context of robust control, specifically the ability of the system to achieve hydropower and food targets when challenged by shocks induced by changes in hydroclimate (extremes) or people (bargaining). The importance of fish and rice for food security in the region was included in our FEW context statement last year. Fish provide more than a majority of the animal protein and vitamin A (>80%,[5]) to one of the largest rural populations in one of the poorest countries of the world (Cambodia) and more broadly to ~60M people in the LMB. Thailand and Viet Nam (combined) export more rice than any single country; larger bodied fish are sold commercially in Southeast Asia, Europe and the U.S. Fish and rice are not only the core of the subsistence livelihood, but also commodities that connects trade across all LMB countries.

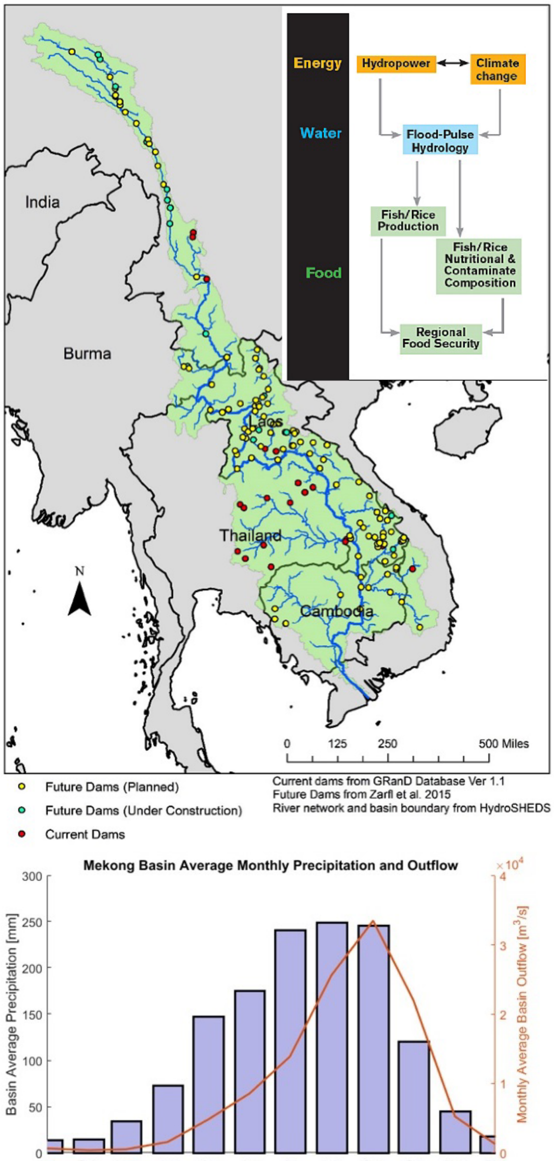
Two points raised in the review require clarification. First, the panel and one reviewer thought that we did not adequately address groundwater in our land surface model. The Mekong is ranked 8th worldwide in terms of *average* annual discharge[6] and more than 75% of that occurs during the three-month monsoon[7]. Newly updated hydrologic models and empirical analyses confirm that surface water drives this flood-pulse (Fig. 2), as well as hydropower, and rice and fish production[8-13]. Groundwater use—especially in the Tonle Sap—is negligible compared to the surface water. While we elect not to alter our modeling strategy, we will be careful to communicate this assumption to our stakeholders. Second, one reviewer was concerned about the amount of data available to understand linkages between rice grain nutritional quality and flood-pulse hydrology. We have clarified that data collection will occur during project Years 1 and 2 during four different rice production periods across at least four different floodwater transects to ensure that we will have the spatial and temporal coverage needed to develop empirical relationships between rice grain quality and key variables. Empirical relationships will also leverage existing literature and laboratory data.

3. BACKGROUND AND FEWS CHALLENGES

The massive Mekong River, one of the world's most biodiverse[14,15], connects China, Burma, Lao PDR, Thailand, Cambodia, and Viet Nam (Fig. 2). Monsoon rains and associated runoff control surface water availability and seasonal flooding (Fig 2; [11]); these in turn support rice production for export and fishery productivity. More than 60 million people in the MRB depend on wild-caught fish and small-scale rice production for their livelihoods.[3,4,16] Indeed, the lower MRB is likely the largest freshwater fishery in the world, with over 2 million tons of fish, valued at ~$2B, harvested annually.[15] Massive changes on the river, including active and planned hydropower development, are at once crucial to the region's economic prosperity and a threat to the fisheries and agriculture that depend on the natural floods.[4,10,14]The MRB is a microcosm of the FEWS challenges facing tropical rivers and large flood-pulse systems globally.

Currently in the MRB, development is driven by individual nations focused on energy and food independence; there is no basin-wide vision. Differing energy demand projections have shaped the national hydropower policies and export plans of Cambodia, Viet Nam and Laos. Given the transboundary nature of the MRB, the development pressures on these riparian nations will only increase challenges to basin-wide management if a socioecological assessment framework is not implemented. Lessons from the MRB tell us that a comprehensive modeling of the F(fishery/rice)EW nexus through the complete socio-physical-ecological pathways is essential for understanding the impact of water management strategies.[9]

River Hydrology under Future Hydropower Development & Climate Change



Current dams from GRanD Database Ver 1.1
Future Dams from Zarfl et al. 2015
River network and basin boundary from HydroSHEDS

Fig. 2. TOP: Mekong River Basin (MRB) including current and planned dams. Inset: prominent modeling linkages established by SMLP. **BOTTOM**: Precipitation drives flood pulse hydrology

The Mekong River is a classic flood-pulse ecosystem[17,18]; surface water hydrology drives ecosystem processes within the channel and surrounding floodplain. Our research builds on macroscale hydrological modeling that uses the Variable Infiltration Capacity (VIC) model.[12,19,20] Early results using late 1990's IPCC climate scenarios and only a coarse spatial discretization suggest that climate change may bring increased precipitation early in the SASM and decreased rainfall later and through the dry season. Both runoff and evaporation increase during most months with increased precipitation. However, most increased precipitation early in the SASM replenishes soil-moisture storage, with minimal streamflow changes. However, this work in now dated and more recent climate studies suggest that climate change will similarly lead to increased precipitation during the SASM, despite a weakening of monsoon circulation[2]; these recent climate simulations have not been used to force macroscale hydrologic models like VIC for the region.

Dam construction and climate change will alter the flood-pulse dramatically.[8,10,21,22] Over 20 hydropower dams are already in place and another 26 are planned for one major tributary alone. These dams are expected to further slow the delivery of the flood-pulse downstream, especially in dams used for hydropower and irrigation. Haddeland et al.[19] implemented a simple irrigation scheme in VIC, which simulated river-water withdrawals based on modeled soil-moisture deficits. Costa-Cabral et al.[12] implemented VIC in the Mekong at a much higher resolution and used a simple (but different) method to represent irrigated paddy rice as a separate land-use class. Both studies demonstrate that irrigation can significantly alter the magnitude of the hydrological fluxes.

Research Challenge: *There is currently a limited understanding of the integrated impacts and tradeoffs associated with dams, climate change, and land-use on the Mekong flood-pulse. Addressing this requires a new, comprehensive, macro-hydrological tool that captures climate-change projections, irrigation of dry-season rice, and the effect of dams on streamflow at the scale of the entire MRB.*

Land-Use and Land-Cover (LULC) Change

The MRB has undergone extensive land-use changes since 1950 due to commercial logging and the conversion of forest lands to agriculture.[23-25] The MRB nations initiated the Forest Cover Monitoring

Project[26], producing the region's first consistent land-cover maps. Currently available LULC maps were generated from NOAA AVHRR data acquired between 1982 and 2000[27]; these cover types are too general. Sawano et al.[28] examined the characteristics of forested area distribution using a MODIS output map,[29] but these data types are outdated, and the maps do not contain major land-use types.

Basin-scale hydrologic models suggest that irrigation could reduce streamflow through increased evapotranspiration (ET)[12,19]; the conversion of riparian forest to agriculture, especially irrigated rice, has substantial impact on water budgets. Similarly, there are no comprehensive measurements of ET for the majority of LULC types, and remotely sensed ET provides macro-scale assessment of rice production. With critical links to hydrologic dynamics and food production, basin-wide LULC and ET must be systematically quantified.

Research Challenge: *LULC changes in the MRB and basin-wide ET measurements are key to understanding current and future hydrologic conditions. Our team will connect new remote sensing techniques to watershed-scale changes in discharge via VIC.*

Climate and Hydrologic Drivers of Ecosystem Production and Fisheries Catch

Flow regime in rivers determines life-history traits, competitive interactions, trophic positions of freshwater species and drives productivity.[30-35]Broad-scale changes to natural flow regimes have homogenized biodiversity[36,37], facilitated biological invasions[34,38,39], and threatened food security.[5,40]The Tonle Sap Lake in Cambodia, the largest inland wetland in SE Asia, is one of the most productive freshwater ecosystems in the world. We believe that this productivity is tied to the SASM through its control on the Mekong flood-pulse.[18,41] However, there are few direct tests of this hypothesis and little understanding of the mechanisms. Previous work in other flood-pulse rivers suggests that discharge variation can explain aspects of primary production, secondary production, and fisheries yield. For example, growth rates and fish recruitment in nursery habitats are higher during years with big floods, high-water, and floodplain inundation. However, the magnitude of the flood-pulse is not the only likely driver; its onset and duration are paramount. Early and prolonged floods provide a longer growing season with a more expansive floodplain, higher resource availability, and lower mortality. These advantages promote somatic growth and size[42-44]and may stimulate the production of multiple cohorts by the same breeding class[45,46] leading to higher biomass. Interannual lags may also be important. In some systems, big, early and long floods improve recruitment, but only when repeated every few years. Finally, low flow leads to low growth or recruitment and low recruitment can persist for large, predatory fishes for several years, until the next anomalously high flood.[44,47] Hence, very high- and low- flows may lead to lagged effects that could override the impact of flood-pulse on fishery yield in any given year. Many potential mechanisms connect flood-dynamics to ecosystem production and fishery catch, and a greater understanding of these processes needed to incorporate flood-dynamics into our modeling efforts.[17,18]

Research Challenge**:** *Ample evidence suggests fish productivity responds to the flood-pulse, yet a mechanistic understanding of these connections is needed for better management. A statistical, data-driven model of flood-pulse to fishery interaction will be integrated into a macroscale water management optimization model to assess the impacts of hydropower decisions on fisheries productivity, a key component of food security and livelihoods.*

Climate and Hydrologic Drivers of Rice Production

Food availability is crucial to food security and human health. Here we follow the USDA definition of food security that considers household-level conditions that may limit access to adequate food, and considers quantity, quality, variety, or desirability of diet.[48] While all four lower basin countries are net rice exporters, yields in Cambodia are the lowest in Asia due to low water in the dry season.[49,50] In the Tonle Sap lowland, one of Cambodia's primary rice producing areas, rice is grown in four different ways determined by flooding extent and duration: (1) Rainfed wet-season rice is restricted to the outer edges of the floodplain where, on average, the land is inundated for only one-month or less per year.[10] (2) Floating rice is grown in floodwater where the land is inundated for 1-5 months annually; it is not highly productive due to irregularity in the lake's hydrologic regime.[50] (3) Recession rice, planted after flooding, depends on captured and retained floodwater. (4) Dry-season rice is grown close to the lake and relies on lake water for irrigation.[50]

Although only 20% of Cambodia's rice production occurs during the dry-season, dry-season yields are higher than wet season yields[50], and the dry-season rice area is expanding rapidly.[51] Dry-season rice farms have encroached on natural grasslands[52], creating water-use conflicts between farmers and fishermen.[47] Dams built on the Mekong will alter rice-cropping patterns and productivity through changing hydrology. Although robust forecasts are not currently unavailable, it is expected that dams will: (1) decrease the extent of maximum flooding, opening up land for wet-season rice production; (2) increase the extent of the permanent lake, and shift the location of dry-season rice production; and (3) reduce the frequency and amplitude of natural interannual flood variations, thus reducing the loss of wet-season crops to flooding, making floating rice a more reliable cropping method, and making the timing for planting of recession rice more dependable.[8,13,53,54] While these changes should largely benefit rice production, they will concurrently reduce the buffer between agricultural fields and natural vegetation and lead to further destruction of natural grassland, likely altering fishery productivity, and potentially increasing conflict between farmers and fishermen.

Research Challenge: *Rice production is a crucial subsistence and economic activity in the MRB. In seasonally inundated areas like the Tonle Sap, rice growing depends on the flood-pulse. Comprehensive water management modeling and forecasts of changes in rice production at local and regional scales under new hydrology are critical components of food security and water resource decision-making.*

Nutrient and Contaminant Fluxes to People via Fish and Rice

Food quality is also vitally important to food security and human health. When rice lacks a single micronutrient, zinc (Zn), and contains a single toxin, arsenic (As), the health of hundreds of millions of people, mostly in developing countries, is adversely impacted.[55,56] Zinc deficiency is a top 20 leading health risk factor identified by the World Health Organization; its health effects include increased risk of diarrheal disease, pneumonia and malaria.[57] Many in the MRB suffer from inadequate Zn intake.[54] Arsenic consumption in rice grain and rice-based food products has been linked with elevated genotoxic effects and cancer.[58,59] Wet-season rice grain from the Tonle Sap lowland contains As at concentrations that pose a threat to human health.[60]

Fish is highly nutritional; it is high-quality protein, and contains important minerals, fat-soluble vitamins, and essential fatty acids. Yet, not all fish are the same in terms of their nutritional quality. Co-PI Holtgrieve established that the top 30 fishery species in the lower MRB vary widely in their fatty-acid composition, with smaller pelagic fishes generally higher in essential Ω-3 and Ω-6 fatty acids[61], and smaller fish generally more nutritious in vitamin A. Similarly, fish differ in their contaminant loads. Our preliminary data on Tonle Sap fish total mercury burdens (THg) suggest that half of the >15 fish species sampled exceed the US EPA Fish Tissue Residue Criterion (TRC), which considers concentration and consumption relative to a reference dose and is designed to protect public health.[62]

We anticipate that dam development and changes to flood-pulse hydrology will alter the nutrient and toxin content of both rice and fish. For rice, grain concentrations of As and Zn reflect, in part, the availability of these elements to the plant root, which is related to soil concentration and chemical form.[63] The migration of rice production into new areas will expose rice plants to soils with different properties (e.g., pH and elements), which in turn vary with flood duration.[8] In addition, shifts in flood-pulse hydrology will alter water access and availability, which will modify water-management strategies. Rice field water management exerts a considerable influence on both As and Zn availability and plant uptake. Yields are highest when rice is grown under continuous flooding[64]; however, continuous flooding establishes highly reduced soil conditions that increase As and decrease Zn availability.[63,65] When rice fields are periodically rather than continually waterlogged, Zn availability and uptake can increase[65] and As availability and uptake can decrease[67], but at the expense of yields.[64] No studies have considered how flood-pulse hydrology impacts rice grain quality, nor assessed the tradeoff between quantity and quality.

Because individual fish species vary in their nutritive value and THg content, and flood-pulse hydrology controls habitat availability, migration, species composition, and catch, we expect that flood-pulse changes will affect nutritional quality of people's food intake through two non-mutually exclusive potential mechanisms: 1) by switching the fish community composition toward species with more or less toxins relative to essential nutrients, and 2) by altering the environmental conditions that determine the availability of nutrients or toxins at the base of the food web. The first mechanism is supported by new theoretical models that suggest the Mekong practice of fishing all species and sizes indiscriminately can skew fish communities toward small, fast-growing species[66,67], which may be more nutritious and have less contaminants due to size and age. This idea has not been evaluated, partly because there are no published data on protein, vitamin, or caloric content for Mekong fishes at the species level. The second mechanism is plausible because, while tropical flood-pulse ecosystems, including the Mekong, are poorly studied with respect to contaminants, they have the environmental conditions for potentially large Hg fluxes, including an abundance of trace metals[68] and high temperature, productivity, and sediment loads. Large areas of highly reducing conditions with extensive flooding and organic matter inputs[69], and a suite of harvested fishes known to inhabit these low-oxygen waters, suggest these are important pathways for moving contaminants to people, especially the rural poor.

***Research Challenge*:** *Little is known about the nutritional quality and contaminant loads of rice and fish in the MRB, or how these concentrations will respond to flood-pulse changes. We will develop a full understanding of how food quantity and quality are connected and influenced by upstream hydropower development and climate change in a critical rice and fish growing area – the Tonle Sap Lake.*

Multiobjective Optimization of Water Resources

The function of modern water resources management in a river basin is to ensure sufficient, affordable, and sustainable supplies of water for humans and natural ecosystems.[70] Water, power, and ecosystem management and planning involve tradeoffs among competing objectives. These days, water resource management is a multi-faceted domain that must incorporate diverse stakeholder needs.[71,72] In the MRB, management is complex due to the confluence of hydropolitics[73,74] and human development pressures that have triggered uncoordinated dam building plans to meet future demand for food and energy.

Multiobjective optimization (MO) supports decision-making processes when multiple—and often conflicting—objectives that reflect the different stakeholders' goals need to be optimized. MO optimizes multiple objectives measured in non-commensurate units[75] and, rather than providing a single optimal solution, unveils existing tradeoffs between objectives by creating a Pareto-optimal curve or surface. Decisions on this frontier are "non-inferior;" they outperform other decisions on at least one objective, and perform equally well or better on the remaining objectives.[76] MO is used to evaluate scenarios in which some objectives (or stakeholders) have more influence by prioritizing and optimizing the objectives in the sequence[77], assigning some more or less importance[78], or setting target values to some objectives while optimizing for others.[79] MO estimates the robustness of optimal decisions to changes in input parameters and to the influence that stakeholders exert on the decision process.

MO has been applied to reservoir management for existing dams as well as dam removal and construction. For multiple reservoir management, objectives range from economic costs and benefits, to water availability and reliability, to hydropower generation and sedimentation control.[80-82] Maximin and minimax objectives reduce the worst-case impacts for water supply and water quality.[83] MO models for coordinated removal or development of a portfolio of dams have typically traded off habitat preservation or connectivity for fish with hydropower and water storage for human consumption.[84,85] Such models have been extended to consider the implementation of a chain of fish passages with less than 100% passability[86,87]; off-channel fish habitat[86]; fish population health, downstream community safety, and invasive species blockage[88,89]; the effect of climate change on water scarcity[90]; and backwater effects on hydropower capacity models.[91] A multiobjective model for the development of 78 dams in the MRB has analyzed tradeoffs between fish abundance, hydropower, and biodiversity, and found that the completion of 78 dams would have "catastrophic impacts on fish productivity and biodiversity".[92]

Research Challenge: *Management of multiple-reservoir systems on river networks is inherently multiobjective, with power, food, safety, and ecological impacts. Developing a computationally tractable yet accurate MO model is critical for assessing tradeoffs between objectives of interest in the MRB.*

Governance, Cooperation, and the Public Welfare

Finally, the delivery of ecosystem services from the flood-pulse to people in the MRB depends on human decisions about resource use. Traditionally, such environmental-governance issues were approached from a monocentric (single governing entity) perspective.[93] Because riparian systems often form the border between governments, and responsibility for decision-making can fragment across multiple units and levels of government, watershed governance lends itself to a multi-actor bargaining perspective.[94-96] The traditional inclusion of governance in quantitative models is based on monetary evaluation, property rights, and price incentives[97]. These factors are insufficient and do not reckon with the influence of alternative institutional arrangements on governance.[93]

Research Challenge**:** Governance of the *MRB watershed requires a broad-based quantitative analysis that accounts for local, national, and regional interests and institutional arrangements.*

4. RESEARCH ELEMENTS

Basin-scale hydrology and water management drive a broad suite of ecosystem functions that, in turn, translate into food and livelihoods (Fig. 1,[98]). To understand the effects of energy-driven hydrologic changes on the food system, we must construct mechanistic linkages among physical drivers, ecological and biogeochemical responses, people, society and governance. Although there is a rich theoretical basis for these linkages, there are few concrete examples.

Our approach is stepwise: First, we explore current and future basin hydrology, water resources, and hydropower on macroscale hydrologic platforms (VIC, WEAP) using a modeling-data platform we have already validated and includes reservoir dynamics. Current flood-pulse hydrologic effects on the food system are elucidated at the local-scale in Tonle Sap Lake through combined field and modeling efforts, and forecasts made through multiple scenarios put forth by stakeholders. Second, with Energy-Water-Food links established, we will use MO to plan coordinated dam operations that meet hydropower and food security objectives and to analyze resilience in the MRB FEWS to adverse climate, political, and economic scenarios. Last, optimization and stakeholders provide constrained scenarios for analysis of potential governance structures in which people cooperate to implement a shared vision. Basin hydrology determined by governance and water resource decision-making connects the regional-scale drivers to local-scale impacts, thereby achieving a cross-scale synthetic analysis that is applicable beyond rice and fisheries and the MRB, to encompass the myriad ways in which humans interact with water systems.

RESEARCH ELEMENT 1: EFFECTS OF HYDROPOWER DEVELOPMENT, CLIMATE CHANGE, AND LULC CHANGE ON HYDRODYNAMICS

We hypothesize that climate change and dams will change multiple aspects of the flood-pulse that are important to ecological function. Warmer temperatures and the conversion of riparian forests to rice paddies will lead to higher water demand.

***A) Macroscale Hydrologic Model* —** For the hydrological model, we will use the VIC macroscale hydrology model (MHM) that has been set up, calibrated and validated (Fig. 3).[11,99-103] For estimation of stream flow, a 0.1 degree resolution VIC Model has been established for the MRB using land cover data from the Global Land Cover Characterization (GLCC) dataset, soil data prepared by the Harmonized World Soil Database (HWSD)[104], vegetation and albedo data from the Moderate Resolution Imaging Spectro-radiometer (MODIS) mission provided monthly leaf area index, while topography information was obtained from Shuttle Radar Topography Mission (SRTM). Our current setup can simulate the streamflow and behavior of existing reservoirs at the daily time step from 2002 through 2017 (16 years) and is already providing nowcasts (Fig. 3). The reservoir dynamics predict reservoir operating behavior (i.e, storage change, outflow and effective rule curve) for 20 large dams of the Mekong based on a unique synthesis of six satellite earth observation datasets.[102] This approach is tailored exclusively for river basins like the MRB where hydro-political hurdles shroud dam operations in secrecy.[11]

Climate — We will base climate-change scenarios on model output from the Coupled Model Intercomparison Project 5 (CMIP5)[105]. We will evaluate, statistically downscale, and bias-correct output from an ensemble of CMIP5 global models. VIC-simulated runoff will be routed through the channel network to selected flow locations to produce daily streamflow sequences, which will be bias-corrected to produce daily natural flow records for the 1950–2100 that can then be input to water-resources models.

Using a technique developed by Vano et al. [106], we will: 1) pre-screen CMIP5 output and select ensemble members to be evaluated, and 2) place the climate-change streamflow time series in context. Final selection of the climate model scenarios will be based on rapid screening [106] and stakeholder input with the overarching goal of facilitating a comprehensive dialogue about the future of the MRB.

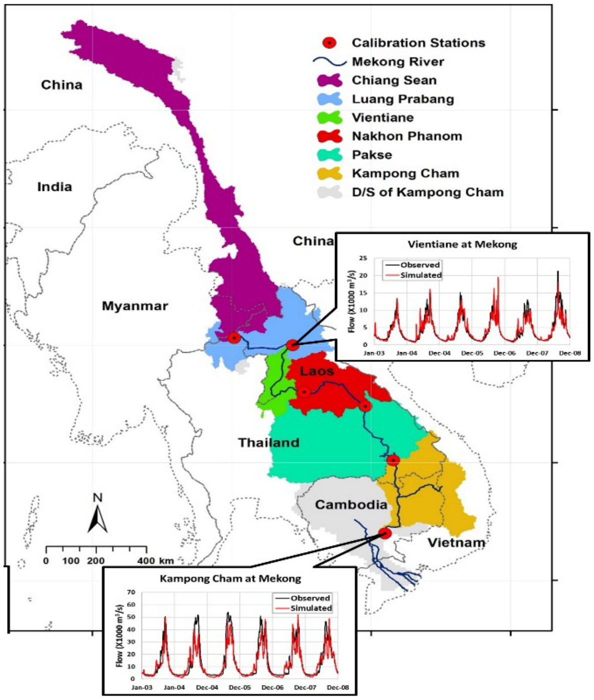


Fig. 3: Validation of predicted streamflow in the LMB using VIC

Water Resources and Hydropower Impact Assessment — We will represent water-resource operations and the assessment of future hydropower planning within our modeling approach in two ways: 1) use the VIC model as a skeleton platform to capture interactions between climate and land use to build water-resource management protocols; and 2) apply a decision-support tool called WEAP (Water Evaluation and Planning) to support stakeholder engagement. We will model the hydropower dams for two scenarios—current and under construction/planned (Fig. 2). The current hydropower dams of Mekong have been characterized in their key physical, hydrologic and operating features in a study by Bonnema and Hossain[11], which will be used as the baseline. We expect that hydropower generation data for current and future dams will be unavailable due to the sensitivity of the information. As a general rule, hydropower generation (P) is proportional to the product of head (H) and streamflow (Q). We will use recommended guidelines on realistic ranges of parameter values as outlined in Shi-Kao et al.[107] for the Department of Energy on new stream hydropower development.

In another approach, WEAP will provide an integrated water resources planning tool for simulating hydropower operations. One advantage of WEAP for stakeholder involvement is that support materials are available in languages other than English (i.e. Chinese, Thai, and Vietnamese). The model has been widely used to develop decision support systems as well as to evaluate climate change impacts on water resources. The model operation can be scripted to evaluate a large number of water resource scenarios. We will use a detailed database maintained by the Mekong River Commission (MRC) on water-development projects in the MRB to assist in setting up WEAP for the basin.

Irrigation Scheme — To simulate realistic irrigation demands under climate change, we will use the CropSyst model[108] coupled to VIC. Here, VIC simulates hydrologic processes, except for transpiration. VIC is modified to simulate crop-specific potential ET and to represent technology-specific evaporation of irrigation water. CropSyst provides transpiration and crop yield as well.

Hydrodynamics of the Tonle Sap — Finally, we will model flood dynamics using an existing 3-D hydrodynamics model.[109,110] VIC-simulated streamflow sequences are a time-varying boundary condition that we will use to simulate flood extent, duration, and biogeochemical parameters such as temperature, oxygen, sediment concentration, and primary productivity. The hydrodynamics model is as yet-uncalibrated for most biogeochemical parameters; we will use existing field data (Miller and Holtgrieve unpublished) to perform this calibration.[8,69]

B) Land-Use and Land-Cover Change — We will use remote sensing and statistical techniques (some developed by Co-PI Myint) to: 1) quantify LULC to improve VIC modeling; 2) estimate ET and linkages with rice production; and 3) calculate NPP for the MRB floodplain. Specifically, we will quantify these parameters in the Mekong Basin over one drought year (2015) and one wet year (2000). We will use coarse-scale MODIS data to provide estimates of wetland extent, riparian forest inundation, and croplands, including land used to cultivate rice. These estimates will be used as system-states for VIC and validation data for the hydrodynamic model. We will also measure change for the TSL using finer-scale data from Landsat and a longer time series of images (5-year intervals, 1985–2015). Finally, we will simulate future LULC change for the entire MRB to couple with the ET model to project water demand given climate change and the conversion of riparian forest to irrigated farmland.

MRB LULC & Cropland Mapping — To better understand how water allocation to rice production has varied between flood and drought years, we will use MODIS data (ideal for its large coverage area and high resolution) to process LULC in the entire MRB. We will focus on a time series of moderate-resolution satellite data with several spectral, spatial, and vegetation bands for large-area mapping. We will undertake rigorous field-plot data collection to generate "ideal spectral" signatures, identify land-cover types, rainfed and irrigated paddy fields, determine crop growth stages, and label classes.[111-113]

Evapotranspiration, LST, and NPP Modeling by Remote Sensing — We will use MOD16, ET estimation by the MODIS Enhanced Vegetation Index models[114,115], as well as MODIS-derived ET by a hybrid direct remote-sensing approach.[114] The final products will be ET maps for the selected wet and drought years. The maps will represent ET on agriculture fields with or without irrigation. By overlaying daily ET map and LULC types, including irrigated and rain-fed rice fields, we will determine the seasonal water demand of rice cultivation in drought and wet years and the differences in ET, land surface temperatures (LST) and carbon flux between 2000 and 2015.

Tonle Sap Lake Region LULC and Cropland Mapping — We will use finer spatial resolution data from Landsat TM imagery to identify detailed LULC trends to inform and update LULC fields in our hydrodynamics model to identify tradeoffs in land use between rice production and fishery yield. From this we will develop LULC models that predict the expansion of irrigated and rainfed rice cropland, building on previous work.[116] We will use a multicriteria decision-making approach using Markov chain analysis[127] and cellular-automata[117] to predict rainfed and irrigated agriculture for 2025. Finally, we will use our estimates of agricultural expansion to project regional future water demand.

The end product from Research Element 1 is a robust modeling framework for reconstructing current flood-pulse dynamics and forecasting future hydrologic conditions and land-use conditions that can be ingested into optimization models to balance water resource tradeoffs.

RESEARCH ELEMENT 2: FLOOD-PULSE TO FOOD SYSTEM INTERACTIONS

We hypothesize that flood-pulse timing and magnitude drives rice and fisheries yield, fish community composition, the rice cropping pattern and growing method, and hence nutrient and contaminant loads to people at multiple temporal scales. We focus on fish and rice production in the Tonle Sap Basin because this location exhibits strong links between ecology and hydrologic drivers, nutrition from fish and rice are arguably the most important ecosystem service, and there are existing models and data to build upon.

A) Connecting Flood-Pulse Dynamics to Fish Production — We will connect the flood-pulse arising from climate change and hydropower operations to the quantity (catch per unit effort, or CPUE), species diversity, and quality (nutrient and contaminant loads) of fish in the TSL using a data driven approach. We will derive a statistical proxy for flood-pulse extent (FPExt) and a spectral measure of discharge variation called the Net Annual Anomaly (NAA) from methods developed by the PI based on the Discrete Fast Fourier Transform (DFFT; [118-120]). Then we will compare this statistical proxy to areal measures of flood-pulse extent in TSL derived from our hydrodynamic model and, where feasible, will use all three metrics to predict fishery yield, biodiversity, and nutrition. We will connect FPExt and NAA to fish yield, species diversity, and nutrition using a novel multivariate autoregressive state space (MARSS) framework.[119,120] This approach will allow us to understand not just how the total yield varies with the flood-pulse, but also how species composition and nutrient and contaminant profiles vary with departures from annual expected discharge. Using this framework, we will assess how characteristics of yield vary at different lags—years after exceptional floods and droughts—and evaluate the effects of changes in the flood-pulse on catch. The PIs (Sabo and Holtgrieve) have already applied these methods in consultation

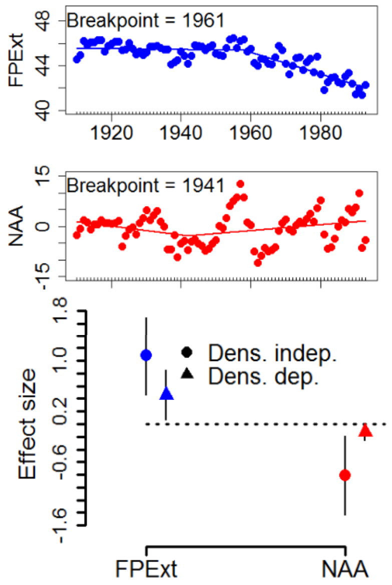


Fig. 4. ***Top two***: Century scale trends in flood pulse extent (FPExt) and the net annual anomaly (NAA), breakpoints with install of first dam on Pak Mun, Thailand. ***Bottom***: Effect of FPExt and NAA on total catch from historical data on the bag net (dai) fishery on Tonle Sap River Cambodia.

with the MRC, and over 100 years of daily discharge data and 16+ years of spatially replicated harvest data for the Tonle Sap River bagnet (dai) fishery (Fig. 4). Our preliminary results suggest that FPExt has a strong positive effect on yield, as we would expect from previous work.[121] NAA has a countervailing negative effect on yield, a result that is explained in part by the positive effect of the interflood interval (IFI). Long droughts (IFI) punctuated by large magnitude floods enhance yield. FPExt has declined and NAA increased since the closure of the first dam on the Mekong system—on Pak Mun in Thailand. *We will use covariate effect sizes from historical analyses in combination with future hydrology (from Research Element 1) to project fish yield, diversity and nutrition under different stakeholder-defined scenarios.*

Data Requirements —We will derive CPUE and fish community data from three sources: 1) ~16 years of commercial fisheries data from the dai fishery; 2) recently initiated comprehensive community fisheries monitoring for CPUE and fish community composition by IFReDI; and 3) parallel monitoring in the TSL by collaborators of a Belmont Form funded project on indiscriminant fisheries (PI: L. Hannah). For field data collection, we will work closely with IFReDI to employ standard CPUE and species-composition methods including independent validation sampling. With these high-quality data, we will have ample sample size (n>30) to implement MARSS. The goal is to enable local fisheries agencies to maintain these sampling efforts to enable quantitative annual forecasts of potential fisheries harvest.

B) Modeling Flood-Pulse Driven Rice Production — We will use the VIC-CropSyst model[108,122] in conjunction with rice cropping maps to simulate rice production scenarios in TSL basin. CropSyst coupled to VIC is a process-oriented crop systems model that can simulate yield, phenology, ET, and nitrogen dynamics of various herbaceous crops including rice using daily weather data and soil properties.[108,123] VIC-CropSyst simulates cropping sequence and crop rotations[116,136], and has been calibrated and tested for simulating different rice varieties and production situations in different parts of the world including South Asia and Europe.[123-126] Its ability to simulate crops in sequence or in rotations will allow us to test different rice cropping scenarios with respect to the timing and duration of flood-pulses. We will calibrate and test VIC-CropSyst to simulate the rice production scenarios in the TSL[50,127] and then apply the model to simulate interactions between rice production and flood dynamics.

Data Requirements —The CropSyst module requires daily weather data (i.e., max. and min. temperatures, precipitation, solar radiation, wind speed, relative humidity), soil properties (e.g., CEC, pH, texture, layers and depth), crop files (e.g., crop and cultivar coefficients), and management profiles (e.g., date and amount of flooding, irrigation and fertilization).[108] We will obtain representative soil, crop and management profiles of the TSL from local collaborators including IFReDI, MRC, and Asian Development Bank Environment Program and, when necessary, literature and field sampling.

Current Estimates and Future Projections of Rice Quantity — We will use outputs from Research Element 1 (flood-pulse hydrology and rice cropping maps for current and future scenarios) to drive VIC-CropSyst to estimate current rice yield in the TSL and to project future changes with dam development.

C) Hydrologic Drivers of Nutrients and Contaminants in Rice — We intend to empirically model Zn and As concentrations in rice grain, harnessing TSL field data (see *Data Collection*) and literature data[8,60,63,128,129] to predict how concentrations of these elements change with soil properties, flood duration and depth, cropping system, and farmer management strategies. We will also incorporate data from ongoing efforts by Neumann and Kim aimed at understanding direct climate effects (i.e., temperature and atmospheric CO_2 concentrations) on As and Zn concentrations in rice grain. If feasible given available data, we will model biophysical and biochemical processes involved in the movement and uptake of As and Zn from the soil to the plant as a complimentary alternative approach.[130-132] After calibration and testing, we will couple the rice quality model with rice production outputs from VIC-CropSyst. The quality model will use climate, soil properties, management, cultivar, flood and cropping system information included into VIC-CropSyst to simulate As and Zn concentrations in rice grain under current and future hydrologic scenarios.

Data Collection — Field research is necessary to generate empirical relationships for the rice quality model. In project years 1 and 2, we will collect soil and mature rice tissue samples (straw, husk, grain) across at least four floodwater transects in the TSL during the four different rice production periods. Output from Research Element 1 will determine flood duration and depth along these transects. At each location, we will gather field management information from farmers, including watering and fertilizer regimes and crop rotations. Following Seyfferth et al.[60], we will obtain representative composite soil (0–20 cm depth) and rice plants samples from at least three locations in each sampled field. We will use standard methods to determine color, particle size, organic matter content, pH and electrical conductivity of soil.[133,134] In an anaerobic glove box, soils will be homogenized and extracted with $CaCl_2$ and acetic acid, with acid-ammonium-oxalate, and with hot HNO_3 to estimate, respectively, plant-available elements, elements associated with poorly crystalline oxides, and total element concentrations.[60,134-136] We will analyze extract solutions with ICP-MS for As and Zn using standard additions[137] and with an autoanalyzer for nutrients using matrix-matched standards.[138] Rice tissue will be dried, weighed, ground, and microwave digested (HNO_3/H_2O_2) for analysis of As and Zn by ICP-MS.

Current Estimates and Future Projections of Rice Quality — This work will expand the capability of VIC-CropSyst for simulating rice grain quality at the landscape scale in response to flood-pulse hydrodynamics and climate-change scenarios. VIC-CropSyst and the nutrient model will simultaneously estimate current rice yield and grain quality (As and Zn) in the TSL and project how these potentially competing factors may change with future dam development and climate change. Rice grain quality and quantity estimated from this work will be added to the nutrient profiling model (Research Element 2E) and the multi-objective optimization (Research Element 3), which will enable quantitative assessment of tradeoffs between rice yield and grain quality, as well as between rice and fisheries production.

D) Nutrients and Contaminants in Fish — The nutritive quality of fish in the TSL relates to their size, trophic level, and species. Different species use different basal resources and habitat (resource pathways), and this has a large effect on their lipid quality (Ω-3 fatty acids) and essential vitamin content.[139,140] Tropical flood-pulse ecosystems have the required conditions for mercury (Hg) methylation, a known neurotoxin, and thus are also likely to be hotspots of Hg trophic transfer. While it is well known that Hg concentration in fish increases with trophic level in aquatic food webs, the relative importance of resource pathways and habitat in driving Hg transfer is less known.[141] Preliminary data from 15 fish species from the TSL do not suggest that trophic level strongly influences fish Hg. This suggests that basal food resources and habitat—which are expected to strongly covary with the flood-pulse—may play a large role in the concentration of Hg found in fishes. We will test the hypothesis that flood-pulse hydrology strongly influences the amount of Hg and key nutritional compounds available to people via fish through both species- and community-level processes,[69,142,143] with the ultimate goal of further quantifying the relationship between flood-pulse hydrology and human nutrition.[142,143] As with rice, simulations of future hydrologic conditions from Reseach Element 1 will allow us to assess impacts and tradeoffs of hydropower and climate on nutrient and contaminant fluxes to people via fish.

Current Related Work and Expected Future Results — This project will benefit from ongoing work by Co-PI Holtgrieve and collaborators, who are using stable isotope data coupled with fatty acid profiles to estimate the percent utilization between phytoplankton and benthic/bacterial resources.[144] This work also is complimented by current graduate research examining flood-pulse controls on ecosystem bacterial productivity, methanotrophy, and autotrophy in lower trophic levels. We expect that fishes with high utilization of bacterial carbon pathways will have relatively higher Hg, less Ω-3 fatty acids, and lower vitamin A compared to pelagic species using a phytoplankton resource pathway. By comparing fish Hg and nutritive components across seasons and with isotopic traces of carbon sources, we will mechanistically relate variation in their quality as food to flood-pulse hydrology. Regardless of any observed link to specific resources pathways or habitat conditions, these data will be the basis of the nutrition profile models in Research Element 2E.

Field Sampling and Lab Methodologies — We will base this work on a set of 5,000+ biologic samples collected from nine sites within the TSL at both high water (Oct–Jan) and low water (Apr-July) from 2010 to 2015.[142,143] We have analyzed 1200+ individual fish samples across 100+ species for $^{13}C/^{12}C$ and $^{15}N/^{14}N$. Of those, ~500 have been analyzed for $^{34}S/^{32}S$ and 250 for fatty acid profiles. We have also analyzed ~530 individuals from lower trophic levels for the same set of parameters. These data inform how species and individuals obtain their resources (e.g. phytoplankton or bacterial pathways), and their seasonal habitat use. We will capitalize on this rich dataset by adding Hg and nutrient content analyses. Total body burden of fish will be determined from muscle total Hg and converted to methyl Hg.[145,146] We will send ~600 tissue samples to Western University, Ontario for Hg analysis. Total lipid and fatty acid analyses will occur in the Holtgrieve lab, while nutrient content analyses will be sent to an independent food testing lab.

E) Nutrition Profiling **—** People in the lower MRB suffer from substantial undernutrition, with both Cambodia and Viet Nam in the upper one-third of countries experiencing stunting and child death.[57,140] To establish the critical link between flood-pulse driven fish/rice production and human well-being, we must quantify how fish and rice satisfy the population's nutritional requirements. We will need to weigh the nutritional benefits of fish and rice consumption against the toxicological risks, both of which are expected to vary with flood-pulse hydrology. PI Drewnowski developed the Nutrient Rich family of nutrient-profile models, which use nutrient content and reference amounts (USDA recommended daily intake[147-149]) of foods to describe their nutritive value.[150-153] We will build on these models to make them specific to fish species and rice crop type, as well as to add a unique toxicology component.

Balanced nutrient-profile indices score nutrients known to be beneficial against those that should be limited. Nutrient profiles can also account for the role of the food in the population's diet, with reference to the needs of pregnant women, young children, and the elderly. The innovation we propose is to supplement the disqualifying nutrients subscore with a contaminant score based on concentration and toxicological data. The positive, or qualifying, nutrients for the algorithm will include, at a minimum, selected macronutrients (protein, fiber, essential fatty acids), vitamins (Vitamins A and C), and minerals (calcium, zinc and iron).[154,155] It is impractical to screen for all possible environmental contaminants in fish and rice. However, because of high background concentrations and frequent reducing conditions, methyl-mercury (meHg) is likely to be a prevalent in meaningful concentrations in fish of the Mekong. There is an extensive literature of health effects of meHg to draw on including neurodevelopmental damage among children exposed prenatally.[156] Nutrient profiling will similarly balance the positive effects of Zn and negative effects of As in rice. Agencies, organizations, and institutions have proposed differing reference amounts for many toxicants and toxins and will thus require synthesis derived from literature searches and stakeholders—a significant work product. *The resulting profiling system will be broadly applicable, in both freshwater and marine systems, for evaluating the nutritional role of fish, and in rice systems where contaminant and mineral information are available.*

F) Projecting Rice and Fish in an Integrated Framework — This element will produce metrics describing yield, functional characteristics, and nutrition of the integrated food system. We will achieve this in a multi-model and model-agnostic way. In section A above we articulated how we will derive *historical* relationships between the fishery and hydrology using DFFT-MARSS and a high-quality observational datasets of fish harvest and discharge. We also described how current and future rice production can be modeled using a land-surface approach (VIC-CropSyst) or techniques that rely on remote sensing products. The effect of the flood-pulse on rice production, functional traits, and nutrition can also be assessed using observational data and the DFFT-MARSS approach. This presents our team with the opportunity to compare tradeoffs between physically based systems (VIC-CropSyst) and statistical approaches (DFFT-MARSS) for forecasting the rice component of the food system. We propose connecting FPExt and NAA to rice production at the scale of MRB and TSL to derive a set of historical covariates describing effect sizes of the flood-pulse on rice yield, functional traits and nutrition—parallel to those derived for fish. Data for this statistical model can be obtained for the MRB (yield by country) from the UN Food and Agriculture Administration and for TSL from interagency agreement through our collaboration with IFReDI. We will then project the entire food system—fish and rice yield, functional traits and nutrition using a MARSS process based on historical covariate estimates and future hydrology obtained from Research Element 1. *This research element will produce food metrics that can be ingested by our optimization algorithms. These metrics are singular for fish (statistical) and multiple for rice (statistical, physically, and satellite based).*

RESEARCH ELEMENT 3: TUNING HYDROPOWER OPERATIONS TO MEET MULTIPLE OBJECTIVES

This element hypothesizes that although hydropower development involves tradeoffs with food production and ecosystem services, hydropower operations can be tuned to meet power generation objectives while satisfying food production and ecosystem service targets in the MRB.

Managing the MRB reservoir network is a complex operational planning problem with much uncertainty and multiple conflicting objectives measured by non-commensurate metrics. We propose an MO approach for multiple dam management and/or new development that simultaneously considers main-stem and tributary dam interactions in terms of hydrology, backwater, sedimentation, fish migration and habitat, flooding, power generation, and irrigation, while optimizing objectives related to hydropower, food production, and ecosystem services. In the MO model, conditions governing the MRB FEWS will be described via constraints, which will be functions of decision variables capturing the hydrograph profile for each dam and the corresponding water flow balance downstream. These constraints will be parametrized based on our findings of the connections between hydrology and energy, food, and ecological services. The MO model will likely be a large-scale model because of the multiple components participating in the MRB's FEWS, thus posing a computational challenge for its solution. To tackle this challenge, we will structure the MO model as a network optimization problem with side constraints, which will allow us to decompose the problem to solve it efficiently.[157-159]

The MO model will not only inform decision-makers on the existing tradeoffs between the objectives, but also allow them to conduct "what-if" analyses to assess how changes in the MRB FEWS setup impact the objectives. These analyses include variations in the importance of some objectives (or stakeholders) (e.g., *what if* the primary objective is power generation?); changes in rainfall or hydrology (e.g., *what if* a drought affecting some tributaries is observed?); changes in land development patterns (e.g., *what if* land use in certain areas drastically shifts to irrigation-intensive rice agriculture?); among others. In general, we will focus on the combinatorial effects of dams on flood deposition and agricultural production, and the resulting tradeoffs between these factors and power generation, which has not been studied previously in either the dam removal or dam development optimization literature. *The outputs of our model will be a Pareto-optimal tradeoff curve (for 2 objectives) or surface (for 3 objectives), where each non-dominated solution represents a hydrograph configuration of dams that satisfy the conditions governing the MRB FEWS.*

RESEARCH ELEMENT 4: MODELING GOVERNANCE OF THE MRB

Analysis of bargaining and cooperative game theory will identify tradeoffs and potential reconciliations among FEW sectors and demonstrate how interactions among actors at different levels of government (basin, country, local) will vary under alternative climate and development scenarios.

To synthesize the impacts of climate change, land use and new dams on lower MRB residents, we will use an economic and game theoretic framework with emphasis on bargaining among actors – national and subnational - with a diversity of interests. This bargaining analysis complements the multi-criteria optimization analysis of Research Element 3 by examining the consequences of interactions among parties instead of optimization for a certain mix of criteria.

An important distinction is the conduct of governance and decision-making *within country* versus *between country*. Depending on politics on the ground, there is an element of hierarchy that can structure decision making on agriculture, fishing or energy by actors within an MRB country. Failing this, since the parties are located within the same country and can enter into enforceable agreements, the appropriate tool for analyzing the bargaining is likely to be cooperative game theory (CGT) and solution concepts such as the core, the nucleolus and Shapley Value. CGT focuses on how the parties to the bargaining could form coalitions to pursue their joint interests, and identifies coalitions that could be both stable and sufficiently powerful to drive through a preferred solution to the bargaining game. In modeling the motivation of within-country actors we will utilize socioeconomic datasets from our partner groups at WorldFish, Conservation International, and MRC.

With regard to bargaining across national boundaries, to the extent that there is the ability to form binding agreements (international river basin treaties), CGT can be used to identify the potential benefits of cooperation and to predict bargaining outcomes. Another alternative is Paretian Analysis,[160] which focuses on identifying undominated alternatives that are candidates for a compromise solution. CGT has been employed to analyze international river basin management on the Ganges, the Nile, the Euphrates, and the Rio Grande.[161-164] It has also been applied in a rudimentary manner as a teaching exercise to the Mekong[165], and also to a sub-basin in Laos.[166]

CGT is well suited to water resource issues since they involve a relatively small number of key actors who are inter-related by geography, creating scope for strategic behavior; the movement of water creates physical externalities; and there are typically economies of scale in water infrastructure.[167] A common application of CGT is cost allocation when infrastructure involves joint costs, and the bargaining focuses on how to share the costs among the parties.[168,169] In these and other cases, the set-up has involved a single dimensional objective function. We will extend the application of CGT to the case where actors have multiple objectives and are faced with tradeoffs among those objectives in the course of the bargaining. To implement this, we will develop multi-attribute utility functions for the major parties[166] either by conducting interviews with major actors or via simulation/sensitivity analysis based on information available to us from our partner groups.

Whether an actor agrees to a proposed bargain depends on how it compares with her baseline, or BATNA, utility (her best alternative to a negotiated agreement). Changes in the BATNA introduce a dynamic element into the bargaining and can affect its outcome. External parties, including higher levels of government, can attempt – if they so wish – to influence the likelihood and nature of an agreement by manipulating a party's BATNA, offering rewards for an agreement and/or punishments for failure to agree. The rewards/punishments need not be monetary, depending on the party's utility function. Parties can also offer one another side-payments – monetary or otherwise – to cement an agreement. High-level external parties (e.g., legislatures) may also be able to intervene by changing the voting rule or the decision-making process. *We will examine the sensitivity of potential bargaining outcomes to such external interventions, basing the selection of interventions to consider on our field research and suggestions from our partner groups.*

5. INTEGRATED MEASURES OF FEWS RESILIENCE

The SMLP will integrate Research Elements 1-4 through novel, integrated measures of resilience. We define resilience as the ability of the social, physical, and ecological system to absorb shocks such as climate extremes.[170] Using optimization models, we will integrate physical and human components, and synthetize water, food (rice and fish), and energy (hydropower) goals. These models will identify plans for spatiotemporally coordinated dam operations that deliver target flows to downstream food production and hydropower. To measure its ability to satisfy such goals, we will optimize the MRB FEW system and design coordinated reservoir operations that satisfice basin-wide food and hydropower production. We will then assess the robustness of these designs by subjecting them to adverse conditions including extreme scenarios of LULC change (conversion of floodplain to crops), simulated basin wide droughts and other extreme climate events, and stakeholders' biases towards certain goals (e.g., power generation). Here resilience is measured as the ability of the system to deliver food and hydropower goals in spite of rapid land use change, drought and sudden shifts in stakeholder objectives. Furthermore, given that the optimization-based solution reflects a centralized ideal MRB operation, we will complement these measures of robustness by incorporating game-theory elements to capture national and sub-national interests, and to explore the benefits that cooperation and bargaining may bring in the achievement of FEW objectives. Ultimately, this study will help us recommend actions at multiple levels—national and multinational—to improve MRB resilience and to mitigate the risk of reaching catastrophic operational thresholds during adverse events that threaten the satisfaction of FEW goals.

6. INTELLECTUAL MERIT

The SMLP will provide an innovative, scalable and model-agnostic framework for predicting the effects of hydropower development, climate change and LULC change and institutional bargaining on the MRB flood-pulse, and tradeoffs between hydropower generation and yields and nutritional quality of fish and rice. This framework involves skillful threading of the widely used macrohydrological model, VIC with hydropower operations and generation (WEAP), projection of food production quality (nutrient and contaminant profiling, MARSS-DFFT), multi-objective optimization achieved via network algorithms and cooperative game theory of LMB institutions. We will optimize model outputs in a way that allows us to design "smarter" operations that satisfice flood-related production of food and power with and without the constraints of the social system—i.e., assuming a no institutional diversity and then, confronting this assumption with the realism of multinational, multiobjective governance.

7. BROADER IMPACTS

Broader impacts will be fourfold: 1) generation of critical data on food quantity and quality; 2) broad stakeholder engagement to co-develop meaningful future scenarios and disseminate results to users; 3) development of a novel online learning platform to enhance STEM for sustainability; and 4) scientific capacity development of researchers and student within the LMB and training of US scientists.

This project will generate critical new data on nutritional and contaminant content in fish and rice from an understudied and rapidly growing region of the world with significant food-related health problems. Such a dataset is essential if UN Sustainable Development Goals[171] are to be met for all inhabitants of the MRB. We will make our data and models freely available to participants and the MRC. PIs Sabo and Holtgrieve's current role as international advisors to the MRC Fisheries Programme will facilitate this effort. We will further collaborate with the East West Management Institute and Open Development Cambodia (see letter) to streamline data access to our datasets that improve sharing and collaboration.

During the three-year project, we will collaborate with IFReDI, MRC, and Conservation International to co-develop our model frameworks and the scenarios addressed in the analyses. We will accomplish this through annual three-day stakeholder workshops delivered in Phnom Penh. The goal of these workshops is twofold: First, we will build trust and credibility by engaging end-users to co-develop credible and relevant scenarios and confront the assumptions of our modeling framework. Stakeholders include crop scientists, fisheries biologists, hydropower operators, scientists from NGOs and multilaterals like Conservation International and the MRC. Second, we will use workshops, carry out a needs assessment, and develop curricula for an online learning platform for training end-users to apply time series models connecting dam operations-hydrology and nutrition in the LMB. In the initial workshop (FY 2018), we will derive input on future scenarios, identify major threats, and build collaborative mental models of the problems stakeholders experience.[170] In follow-up workshops (FY 2019 and 2020), we will gain feedback on our analysis and conduct a needs assessment that articulates skills required for our training module.

Sabo will collaborate with EdPlus—ASU's online learning platform—to develop modules that cover: 1) basic training in statistical analysis; 2) advanced training in time series analysis; and 3) applications focused on LMB natural resource questions. Sabo has already filmed over 40 hours of lecture material, developed companion data and code in R and delivered these instructional materials in a blended learning environment to graduate students at ASU. The goal will be to develop proficiency in interpretation and application of DFFT-MARSS, with a target of reaching at least 20 scientists across the lower basin.

Developing scientific capacity in the lower MRB is crucial to sustaining water resources and ecosystems. In collaboration with Conservation International and the MRC, we will conduct workshops in Year 3 to engage MRB scientists beyond our immediate collaborators to familiarize them with the advanced modeling systems employed for the project. We will also assist our collaborators in applying for USAID Partnerships for Enhanced Engagement in Research funding so they can visit the US, gain modeling proficiency, and continue their work beyond project duration. Our project will also build future scientific capacity locally by training at least two MRB students annually; Holtgrieve and his students/postdocs have previously worked with four Cambodian MS students at the Royal University of Phnom Penh on research projects. We will also train up to six US graduate students, three postdocs, and two early-career scientist (pre-tenure) with no previous NSF research funding