Gallagher, L., B. Kopainsky, A. M. Bassi, A. Betancourt, C. Bun, P. Chan, S. Costanzo, S. St. George Freeman, C. Horm, S. Khim, M. Neang, N. Rin, K. Sereyrotha, K. Sok, C. Sovann, M. Thieme, K. Watkins, C. A. Wyborn, and C. Bréthaut. 2020. Supporting stakeholders to anticipate and respond to risks in a Mekong River water-energy-food nexus. *Ecology and Society* 25(4):29. https://doi.org/10.5751/ES-11919-250429

*Research*

# Supporting stakeholders to anticipate and respond to risks in a Mekong River water-energy-food nexus

*Louise Gallagher*[1], *Birgit Kopainsky*[2], *Andrea M. Bassi*[3,4], *Andrea Betancourt*[5], *Chanmeta Buth*[6], *Puthearath Chan*[7], *Simon Costanzo*[8], *Sarah St. George Freeman*[9], *Chandet Horm*[6], *Sandab Khim*[10], *Malyne Neang*[11], *Naroeun Rin*[6], *Ken Sereyrotha*[12], *Kimchhin Sok*[11], *Chansopheaktra Sovann*[13], *Michele Thieme*[14], *Karina Watkins*[15,16], *Carina A. Wyborn*[17] and *Christian Bréthaut*[18]

ABSTRACT. The water-energy-food nexus concept is criticized as not yet fit for deeply integrated and contested governance agendas. One problem is how to achieve equitable risk governance and management where there is low consensus on priorities, poor inclusion and coordination of risk assessment procedures, and a weak emphasis placed on cross-scale and sectoral interactions over time. Participatory system dynamics modeling processes and analyses are promising approaches for such challenges but are currently underutilized in nexus research and policy. This paper shares our experience implementing one such analysis in the Mekong river basin, a paradigmatic example for international nexus research. Our transdisciplinary research design combined participatory causal loop diagramming processes, scenario modeling, and a new resilience analysis method to identify and test anticipated water-energy-food risks in Kratie and Stung Treng provinces in northeastern Cambodia. Our process generated new understanding of potential cross-sectoral and cross-level risks from major hydropower development in the region. The results showed expected trade-offs between national level infrastructure programs and local level food security, but also some new insights into the effects local population increases may have on local food production and consumption even before hydropower developments are built. The analysis shows the benefit of evaluating risks in the nexus at different system levels and over time because of how system dynamics and inflection points are taken into account. Additionally, our case illustrates the contribution participatory system-thinking processes can make to risk assessment procedures for complex systems transitions. We originally anticipated that any new capacity reported by partners and participants would come from our modeling results produced at the end of the process. However, participants in the modeling procedures also found the experience powerful the information sharing, rapid risk assessment, and personal learning it enabled. A lesson from our experience reinforces a message from the transdisciplinary research field that has not yet been absorbed into the nexus research and policy field wholeheartedly: we do not have to wait for perfect data and incontestable results before making a positive contribution to anticipating and responding to risks that emerge from nexus relations if we apply participatory and systems-thinking informed approaches.

Key Words: *Cambodia; Mekong; participatory research; resilience; risk; scenario analysis; system dynamics modeling; water-energy-food nexus*

## INTRODUCTION

Nexus thinking is a call to overcome tunnel vision. It asks us to critically analyze water, energy, and food resource interconnections and anticipate how changing water-energy-food interactions may instigate, accelerate, or intensify complex system transitions (e.g., Scheffer et al. 2012) and other risks (Hoff 2011). Yet, while considered promising, nexus thinking is currently criticized as not "fit for purpose" when it comes to real situations of deeply entangled and contested governance agendas (Al-Saidi and Elagib 2017).

"Risk" is the probability and severity of consequences from changing framework conditions, for example, in system regimes that affect hazard likelihood, exposure, and vulnerability (Haimes 2009). In the nexus, such consequences manifest differently across actors, scales, and time frames and depend on factors like severity of risk events, who is affected, and their risk tolerances (Gallagher et al. 2016, Grafton et al. 2016). How is risk assessed and allocated fairly where there is low consensus on priorities, problems, and varying vulnerabilities (Weitz et al. 2017)? Recent water governance research (Bouckaert et al. 2018, Pahl-Wostl 2019) underscores the importance of engaging with such uncertainties (Guston 2014) but nexus research has a less developed theoretical focus on adaptive governance. Computational modeling dominates this field (Albrecht et al. 2018, Shannak et al. 2018). Such methods help anticipate some consequences of water-energy-food interconnections but do not consider stakeholder perspectives deeply, if at all (Al-Saidi and Elagib 2017, Hagemann and Kirschke 2017, Larcom and van Gevelt 2017).

We consider that risk assessments in nexus research and policy need to grapple with uncertain and unknown stakeholder values

---

[1]Institute for Environmental Sciences, University of Geneva, Switzerland, [2]System Dynamics Group, Department of Geography, University of Bergen, Norway, [3]KnowlEdge Srl, Olgiate Olona, Italy, [4]Stellenbosch University, Stellenbosch, South Africa, [5]Formerly affiliated with Luc Hoffmann Institute, IUCN Conservation Centre, Gland, Switzerland, [6]WWF Cambodia, Kratie, Cambodia, [7]General Secretariat of the National Council for Sustainable Development, Ministry of Environment, Phnom Penh, Cambodia, [8]University of Maryland Center for Environmental Science, Cambridge, USA, [9]Department of Civil and Environmental Engineering, University of Massachusetts Amherst, USA, [10]General Secretariat of the National Council for Sustainable Development, Phnom Penh, Cambodia, [11]ECOLAND Research Centre, Royal University of Agriculture, Phnom Penh, Cambodia, [12]Previously General Secretariat of the National Council for Sustainable Development, Phnom Penh, Royal Government of Cambodia, [13]Royal University of Phnom Penh, Phnom Penh, Cambodia, [14]World Wildlife Fund, Washington, D.C., USA, [15]UK Foreign, Commonwealth and Development Office, [16]Formerly affiliated with WWF Cambodia, [17]Institute for Water Futures, Australian National University, [18]Institute for Environmental Sciences, UNESCO Chair on Hydropolitics, University of Geneva, Switzerland

and capacities (Yung et al. 2019) and varying risk perceptions (Howarth and Monasterolo 2017, Weitz et al. 2017), as well as changing states of the system being studied (Scheffer et al. 2012). In this paper we share our experience innovating on one method with great potential in this regard at a sub-basin scale in the Mekong river basin in Southeast Asia.

The LIVES project (http://livesproject21.org/) set out to conduct fundamental research on mixed methods approaches for identifying indicators that reflect interdependencies between food, energy, and water and develop understanding of social-ecological system inflection points. Our goal was to innovate a knowledge coproduction method that enables diverse stakeholders to be actively involved in identifying these indicators and inflection points while creating new understanding of trade-offs from multiple actors' perspectives and momentum for seeking solutions. Our departure point was to devise a participatory model-based scenario planning approach based on both futures and resilience thinking (Walker et al. 2004, Foran et al. 2013, Gerritsen et al. 2013, Guston 2014, Boyd et al. 2015, van der Voorn et al. 2017) with scope to include multiple stakeholders (Weber 1997, Klinke and Renn 2012) in a flexible yet robust research process (Rijke et al. 2012, Pahl-Wostl 2019). Our research takes up the thread of Foran et al. (2013), Foran (2015), and Smajgl et al. (2016) with model-based scenario planning assessment of hydropower development in one landscape in Cambodia.

It has been argued that participatory system dynamics modeling has potential to create new knowledge about risks that is accepted by stakeholders as their knowledge (e.g., Basco-Carrera et al. 2017). Some sustainability science research supports this supposition (Innes and Booher 2010, Clark et al. 2016, Rouwette 2016). Well implemented, participatory research can certainly contribute to flexible strategies that consider long-term goals and consequences under several possible futures (Gerritsen et al. 2013, Guston 2014, Boyd et al. 2015, van der Voorn et al. 2017). Yet, we still struggle with including stakeholders from outside the technocratic policy world effectively and fairly (Voinov et al. 2016, Jordan et al. 2018). With these challenges firmly in mind, the specific objectives for our three-year process were the following: "

1. Elicit and integrate knowledge from diverse stakeholders in the landscape."
2. Assess direct and indirect, short- and long-term consequences of rapidly changing framework conditions relevant to subnational development planning by identifying major variables and interconnections and exploring dynamic complexity in the landscape."
3. Learn how to enhance agency for individuals and collectives who participated through training on participatory model-based scenario planning methods and expanding networks.

We report a reflexive analysis of results and feedback from our partners and participants as a contribution to continuing innovation in nexus research. Rather than applied research, we consider this work a contribution to fundamental research on nexus methods because of its novel characteristics. Where other Mekong nexus studies advance horizontal policy and actor network integration at national and basin-scales (Foran et al. 2013, Smajgl and Ward 2013, Smajgl et al. 2015, 2016, Pittock et al. 2016), we explored both vertical and horizontal integration between national and provincial-levels in participatory risk assessments. The explicit risk lens in our study is rare in empirical nexus research (Grafton et al. 2016), and our chosen computational modeling method, system dynamics modeling, has not yet been applied in the Mekong region in participatory form (Bassi et al. 2016, Chapman and Darby 2016, Pittock et al. 2016) to the best of our knowledge and has some interesting complementarities to participatory agent-based modeling approaches previously tested in the region (e.g., Smajgl et al. 2015).

## CASE DESCRIPTION

The Mekong is a busy testing ground for conceptual and analytical frameworks in nexus research (Foran et al. 2013, Smajgl and Ward 2013, Foran 2015, Middleton et al. 2015, Smajgl et al. 2015, Pittock et al. 2016, Lebel and Lebel 2018) because it is a region where large-scale, uncoordinated hydropower development, climate, and socioeconomic change converge in a biodiverse social-ecological system to impact on livelihoods, water, and food security (Molle et al. 2012, Middleton et al. 2015, MRC 2017, Fox and Sneddon 2019).

Two provinces in northeastern Cambodia, Kratie and Stung Treng provinces, have been experiencing rapid change through forest clearance for rubber plantation, river bed sediment mining, road network infrastructure, and climate change impacts (RGC 2011*a, b*). The provincial administrations comanage parts of the Mekong Flooded Forest Landscape, a transboundary biodiversity conservation landscape hereafter referred to as the MFF Landscape (Champasak province in neighboring Lao PDR is also part of the landscape but is excluded to focus on Cambodian jurisdiction in this research). At the time of this research, two major Cambodian hydropower projects, Stung Treng dam (Stung Treng province) and Sambor dam (Kratie province), were at proposal stage with physical construction imminent in the landscape though with little information being shared publicly with local communities. Both projects are currently on hold under the new moratorium on hydropower development in the central Mekong channel in Cambodia (Ratcliffe 2020).

Increased energy supply is a priority under the Royal Government of Cambodia's development plans because of high domestic energy costs and low rates of energy access (RGC 2016*a, b*). Hydropower is considered to be the main domestic renewable energy option available to improve energy security (RCG 2016*a, b, c*). From the provincial administration, commune administration, and community perspectives, the change in the Mekong River's flow means unpredictable change to the flood regime, fish migration patterns, and biodiversity given observed climate change effects (RGC 2016*d*, MRC 2017).

Risk-based management is limited in Cambodia with low availability and sharing of local risk information (Mochizuki et al. 2015). This fact, along with differences in local and national priorities, power differentials, and other complex cultural, political, and historical factors domestically (Milne and Mahanty 2015) and regionally (Molle et al. 2012, Urban et al. 2015, Villamayor-Tomas et al. 2016) means risks and opportunities are assessed most consistently by powerful national line ministries in relation to regional energy market dynamics, energy security, and industrial development. The result is a poor consideration of how dams could contribute to local, national, and regional food, livelihoods, and other insecurities (Sithirith 2016).

## METHODS

Our transdisciplinary research design (Lang et al. 2012) applied participatory system dynamics modeling (Videira et al. 2010) and a new resilience analysis method (Herrera 2017) to analyze anticipated water-energy-food risks in Kratie and Stung Treng provinces. We identified major elements in the local water-energy-food nexus structure with stakeholders—the variables and interconnections that are relevant to understand water, energy and food production and stakeholder priorities and perceived risks—and then analyzed the development and resilience of these under various scenarios.

## RESEARCH TEAM PARTNERS

The General Secretariat to the National Council for Sustainable Development (NSCD) was our national government partner. NSCD is a key stakeholder because of their position as a cross-ministerial body with the mandate to prepare, coordinate, and monitor implementation of policies, strategies, legal instruments, plans, and programs related to sustainable development in Cambodia. Other key partners included WWF Cambodia, a civil society organization operating in the MFF Landscape, the Royal University of Phnom Penh (RUPP), and the Royal University of Agriculture (RUA)—civil society actors active on the water-energy-food and biodiversity trade-offs both nationally and in the case provinces, with networks and legitimacy to convene government actors, local communities, and local civil society organizations in Kratie and Stung Treng provinces. WWF, with their long-standing engagement structures and relationships with the NCSD, the Ministry of Environment, and both provincial administrations, issued the formal project workshop invitations and managed project stakeholder networks.

## STAKEHOLDER IDENTIFICATION

Our stakeholder identification procedures were implemented iteratively throughout our research process. The partners agreed that an essential starting point was to begin with actors with a stake in development planning processes at commune level in the MFF Landscape.

National development and commune investment planning processes are the formal governance mechanisms both anticipating and driving changes in economic, social, and environmental conditions in the provinces. However, the planning process is fragmented across several national line ministries. In theory, local-level priorities are identified in the long-standing Commune Investment Planning (CIP) processes, guided by Ministry of Interior rules on procedures, and rolled up through district and provincial administration departments to their national line ministry and integrated in National Strategic Development Plan (NSDP) every five years. In practice, little horizontal or vertical integration takes place in planning (Vuković and Babović 2018) and there are concerns about how the process works in practice (World Bank and The Asia Foundation 2013, Siciliano et al. 2015). A process of decentralization and deconcentration of government functions (hereafter: D&D reforms) is devolving some national line ministry functions from the national Ministry of Environment to the Provincial Departments of Environment, though public finance is still centralized at national level (Vuković and Babović 2018). Between the CIP and its development outcomes (World Bank and The Asia Foundation 2013) and the emergence of the provincial level as a new significant jurisdictional scale, the research team identified the provincial government administrations as a critical group of stakeholders to work with on the MFF nexus assessment.

Provincial administrations are actively requesting support to develop new capacities to undertake new mandates being received under D&D reforms. This perhaps explains the consistent attendance of government officials from 10 departments and executive-level offices in provincial administrations, including the Deputy Governor offices in our research process. These actors also represent business and broader community interests to some extent, given that low government salaries means essentially all government employees can be assumed to have some other economic interests ongoing: farming, commerce, property investment. D&D provincial program representatives from the national Ministry of Interior participated in every workshop. We invited local civil society groups to participate alongside local government participants in representing these community concerns. At later stages in the research process we invited farming and fishing community representatives to separate workshops (reported in Kimmich et al. 2019). We did this in awareness of power dynamics arising from visible and invisible social, political, and cultural structures (e.g., Bréthaut et al. 2019) and power distribution in research processes (e.g., Pohl et al. 2010), which can influence what information is shared and how it is interpreted in wicked problem contexts (Parkhurst 2016) where data poverty is a concern (Johnston et al. 2013). We ran all workshops in Khmer, with a mix of facilitators from the government, civil society, and academic partners. We held separate events for different stakeholder groups where we thought hierarchy would influence contributions. We requested anonymous feedback surveys at the end of each workshop. All research team partners participated as knowledge contributors when not fulfilling the roles of trainers or facilitators.

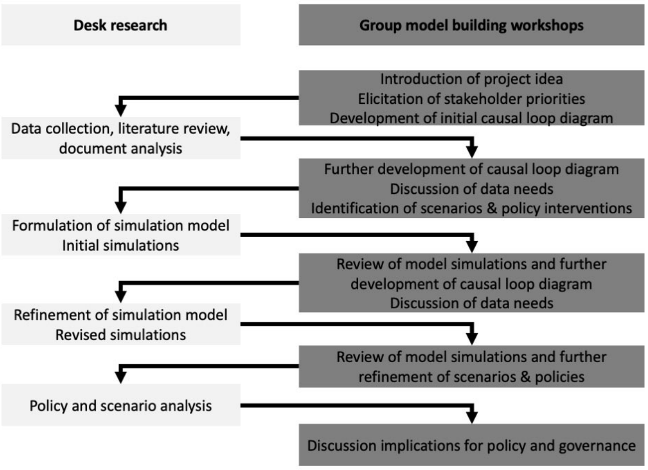
## PARTICIPATORY SYSTEM DYNAMICS MODELING PROCEDURE

System dynamics modeling creates explanatory models of system structures and simulates dynamic interplay between key variables to explore system behavior over time (Forrester 1961, Sterman 2000). The method helps system conceptualization and problem identification in social-ecological systems where simulation, not optimization, is most useful for decision making (e.g., Videira et al. 2010, Kopainsky et al. 2017). Such models facilitate knowledge integration across many domains (Harwood 2018), shedding light on interactions between social and natural systems and how these might be influenced by public policy (Ghaffarzadegan et al. 2010).

### *Summary of participatory modeling procedure*

The system dynamics model was developed using a participatory modeling procedure (Fig. 1). We identified and quantified the mechanisms underlying trade-offs between national level energy security and economic growth and local level food security, the priority risks (scenarios), and potential actions (interventions) in an iterative process between stakeholder engagement and desk research. Stakeholder engagement involved five participatory group model building workshops held between Phnom Penh, Kratie, and Stung Treng between January 2015 and July 2016, bilateral meetings, and additional expert interviews to close knowledge and data gaps. Other follow-up workshops with local farming and fishing communities included a small number of provincial officials during 2017. A final workshop was held in Phnom Penh in December 2017 where preliminary analysis results were presented to national government representatives from Ministries of the Interior, Environment, among others (see Appendix 1 for a detailed overview of meetings).

**Fig. 1**. Participatory modeling procedure with stakeholder workshops and desk research.



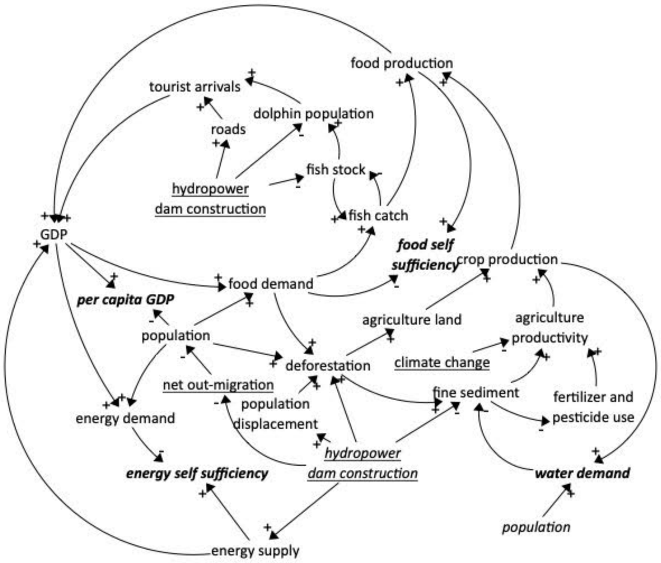
*Identifying causal links, risks and possible interventions*

Stakeholders coproduced multiple causal loop diagrams (CLDs; Hovmand et al. 2012, Voinov et al. 2016), identifying major variables and interconnections that characterize the dynamic complexity of the MFF landscape, including the major nexus interrelationships between water, energy, food resources, and links with ecosystems.

The nexus concept was new for all our stakeholder groups, as was the CLD procedure. A team of national researchers, national government staff, and local WWF staff were trained in facilitating preliminary values and threats analysis and CLD scripts, working alongside international researchers to facilitate discussions in Khmer. Following Luna-Reyes et al. (2006), stakeholders' CLDs were analyzed to elicit (i) stakeholder assumptions, perceptions about critical variables for the MFF nexus, and their interactions; (ii) priority concerns held by these stakeholders; and (iii) possible intervention points that were then aggregated and used to inform the computational model-building.

Figure 2 illustrates the aggregated output of these procedures across all stakeholder workshops. It illustrates the interconnections between water, energy, and food security, as well as economic growth, and a series of critical feedback loops. A first feedback loop connects an increase in crop production with an increase in gross domestic product (GDP). This, in turn, stimulates food demand. Parts of increased food demand are covered by increasing deforestation, which leads to an increase in agricultural land and thus to crop production. Ceteris paribus, this feedback loop reinforces food production and economic growth. A second example of a feedback loop described in Figure 2 is the balancing mechanism introduced by an increase in food demand, which leads to an increase in fish catch and a corresponding decrease in fish stocks. Declining fish stocks erode the food base for dolphins that are an important attractor for tourism. With declining dolphin populations, tourist arrivals go down and therefore reduce GDP. This balancing feedback loop limits the growth of the reinforcing feedback loop between food production and GDP. Validation procedures in this process included prioritizing multiple mentions of similar themes and comparison with other data sources relevant to the Mekong Nexus (e.g., Pittock et al. 2016, as per recommendations of Voinov et al. 2016).

**Fig. 2**. Simplified aggregated representation of the stakeholder-produced causal loop diagrams informing the structure of the water-energy-food nexus in the Mekong Flooded Forest Landscape model (key risk indicators highlighted in ***bold and italics***).



The full CLD developed with stakeholders includes a large number of feedback loops that all interact with each other. For scenario and policy analysis, it is thus important to quantify the relationships described in the CLDs and translate them into a running simulation model, hereafter referred to as the MFF mode.

*Model description, data, validation, and limitations*

The MFF model simulates water-energy-food interactions for Kratie and Stung Treng provinces from 2000 to 2040 with local central river channel hydropower dam construction as the primary trigger for risks. Model equations were sourced from existing models, peer-reviewed papers, and technical reports and iterative consultation with regional, national, and provincial stakeholders and other experts (see Appendix 2). Both system-wide and sectoral calibrations were performed. The model was validated (Barlas 1996) through formal structural and behavioral validation as well as stakeholder review of simulation results during 2016 and 2017. The model is appropriate for aggregated analysis of governance

**Table 1**. Scenarios for the Mekong Flooded Forest Landscape nexus.

| Scenarios | Description and key assumptions |
|---|---|
| Scenario 1: Baseline, without dam | This scenario describes the development of the two provinces in the time frame 2000 to 2040 under the assumption that the current trends and drivers of change remain dominant in the future as well. No new large or exceptional projects are implemented, including any hydropower dams. This is a counterfactual scenario because dam constructions are currently under way. Nevertheless, this assessment of baseline trends is important to assess the multidimensional impacts of hydropower dam constructions. |
| Scenario 2: Baseline, with Stung Treng Dam | The baseline with dam scenario follows the planned capacity expansion of the Stung Treng hydropower dam (980 MW of capacity, 4870 GWh/year of production). In this case, the required reservoir is expected to inundate 211 km² (21,100 ha) of land and lead to 21 villages, some 2000 households being displaced. It is assumed that these households are most likely to be farming and fishing households that would seek to take up similar livelihoods, as has been observed in other cases of outward migration due to environmental and social change in Cambodia (Bylander 2015). A maximum of 15% of the total electricity output is assumed to be distributed to the local population, given that power purchase agreements in this region result in much new energy supply being sold to Vietnam and Thailand (IRENA 2018). Infrastructure expansion, e.g., roads, happens in parallel to the expansion of power generation. |
| Scenario 3: Stung Treng Dam + Higher yield (Adaptation scenario) | This scenario assumes further productivity increases in rice production. Cambodian rice farming practices and yields vary significantly at the individual farm scale but at the aggregate level, rice yields doubled from 1997 to 2016 (1.8 t/ha to 3.4t/ha) due to a combination of fertilizer use, better land and water management practices, and increases in dry-season production, which yields more rice (Ly et al. 2012, 2016, UN FAOSTAT 2018). This scenario assumes a further doubling between the years 2020 and 2040. |
| Scenario 4: Stung Treng dam + E-flows (Mitigation scenario) | This scenario assumes the implementation of an environmental flow standard in dam design and operations (Poff and Matthews 2013, Thompson et al. 2014) to reduce decline in fish stock and negative impacts this decline has on nutrition security, food prices, and dolphin populations. We assume a weak effect because e-flow designs will not offset dam effects on the landscape completely. Their effectiveness depends on many factors (magnitude in deviation from baseline water quantity and timing, adjustments for seasonal variability, willingness and ability to engage in adaptive dam operations, extent to which the dam operates on a peak energy demand basis; Richter and Thomas 2007). This scenario assumes a smoothing out of energy production across the Southeast Asian wet (monsoon) and dry seasons, enabling a net increase in hydropower production while still meeting e-flow standards (Babel et al. 2012). |

responses to be negotiated and agreed, e.g., improve crop yields, but is not yet suitable for policy design in its current form, e.g., deciding levels of investment in crop breeding. Our priority is to understand the main interactions between water, energy, food, and other important dynamics first to identify the main risks and main potential unanticipated consequences of interventions arising from system structure and behavior. The MFF model has two important limitations in this regard: (i) it is not spatially disaggregated, nor is it possible to simulate the behavior of individuals or households as with agent-based modeling; (ii) a poor representation of health domain participants in our process means health variables are weakly represented in the model.

## ANALYSIS APPROACH

Our analytical strategy uses three distinct procedures.

1. Qualitative data analysis. A substantial amount of qualitative data was amassed during the project and analyzed to support the choice of indicators to represent stakeholder priorities and identified risks of concern (hereafter: risk indicators), scenario formulation, resilience analysis design, and in the discussion of results. Interviews with provincial administration officials, were conducted in 2015 and again in 2017 (document code: CA). Workshop reports and stakeholder feedback sheets (document code: SF) were also produced. In addition, 15 Most Significant Change interviews (Dart and Davies 2003) conducted in November and December 2017 elicited project partners' observations about overall changes catalyzed by the research (document code: MSC; see Appendix 1).

2. Scenario analysis. We analyzed outcomes for stakeholder priorities from changing framework conditions triggered by the Stung Treng hydropower development by comparing simulation runs using Vensim simulation software (note that the figures were produced using Stella software). In total, we created four scenarios for analysis. See Table 1 for a description and key assumptions for each.

We calibrated two baseline scenarios, one scenario without the dam and one for future development in the region with Stung Treng Dam. This assessment of baseline trends is important to assess the multidimensional impacts of hydropower dam construction. We focused primarily on Stung Treng dam because at the time of our workshops the construction time line of Sambor dam had not been confirmed. Sambor dam is treated as an "additional hydropower investment" in the resilience analysis. Provincial officials view infrastructure development as a critical enabler of new inward investment flows to the region (CA2015_1). Stung Treng dam is assumed to trigger more natural resources extraction and consumption, and new business activity, in our CLD groups, though stakeholder attitudes to dam development were mixed. There was some confusion about the planned timing and actual sites, and whether the dams will supply domestic or regional energy markets. Stung Treng dam, a proposed mainstem (central river channel) gravity dam, is primarily intended to produce energy for export to Thailand. Sambor dam is communicated as a far-distant development project rather than an impending reality by senior provincial government officials (MSC3). The project team agreed to work with what provincial administration officials have understood from national line ministries as assumptions in model building and explore them in the simulation results: (i) dam construction would employ local workers, (ii) some new power capacity created by the hydropower developments could be redirected to the local economy, and (iii) supporting roads will market access for local agricultural products.

**Table 2**. Resilience analysis for the Mekong Flooded Forest Landscape.

| Disturbance | Disturbance descriptions and assumptions |
|---|---|
| Disturbance 1: Climate Change | We maintain longer term rainfall trends but increase variability in the model to approximate a higher frequency of droughts and a continuous seasonal shift for agriculture production that has been forecast for this region of Cambodia (Mekong Wetlands Biodiversity Conservation and Sustainable Use Programme 2005, ICEM 2015, RGC 2016*d*, Thilakarathne and Sridhar 2017). The analysis varied rainfall minimums (between 50% and 150% of the historical average) around average rainfall projections from climate models to change the uniform random distribution of rainfall variability. Weather variability and extreme conditions reduce yields and productivity of agricultural systems, thus reducing food availability (Schipanski et al. 2016). The potential reduction in yields is particularly important for communities that depend on local production to access food (Thomas et al. 2013). |
| Disturbance 2: Population growth | We varied the magnitude of net migration rate from 2% to 4% (baseline value: 2.7%) for the population disturbances. The model calculates population as a function of the net birth and migration rates. Net migration is partly determined endogenously in that an increase in employment opportunities in the region decreases out-migration, and vice versa. Net migration is also determined exogenously in that it depends on employment opportunities in other regions of Cambodia and in neighbouring countries of Vietnam and Thailand. These exogenous factors clearly affect our case study region so we tested for the resilience of our model results to changes in population. |
| Disturbance 3: Future dam development | Scenarios 2-4 reference the Stung Treng dam alone because this project was confirmed in 2015 and 2016 during the stakeholder workshops. Additional dam projects are on the way however. One important example is the Sambor Dam (Wild et al. 2019). We included a resilience analysis of additional dam investments to account for future dam developments using technical specifications mentioned in Wu et al. (2010). We varied additional investment in hydropower, translating this into hydropower capacity ranging from zero to twice the amount of the Stung Treng dam output. |

Second, we assessed two scenarios for adaptation (an alternative cropping scheme) and a mitigation (environmental flow standards) options to mitigate and respond to risks being created in this local manifestation of the Mekong nexus. The mitigation and adaptation interventions were identified by two separate stakeholder groups. Crop and fish production interventions were identified by both provincial administration stakeholders and farming community representatives in mixed CLD sessions (SF5.1_2017.03.13.), with crop interventions targeting increased rice yields as is heavily promoted by national government policy (Ly et al. 2012, 2016, UN FAOSTAT 2018). Environmental flows technologies were proposed by WWF staff as one mitigation approach to explore, as per Poff and Matthews (2013).

3. Resilience analysis. Given uncertainties surfaced in stakeholder discussions and model calibration, we complemented the model-based scenario analysis with a resilience analysis.

Critical future system disturbances of concern to the national government, provincial administration, and civil society stakeholders were climate change and population dynamics. Civil society groups were also concerned about additional dam investments for Sambor dam being represented in the analysis. For the purpose of our analysis, these disturbances are defined (see Table 2) as (a) a change in rainfall variability (climate change); (b) change in the absolute population growth rate; and (c) additional investment levels beyond the Stung Treng dam, anticipating the potential Sambor dam development.

We analyzed the amount of disturbance (deviation from scenario assumptions) needed to change the MFF system from the starting simulated scenario state to another state using two specific resilience metrics (as per Herrera 2017): "

1. Hardness, or the amount of disturbance that a system can withstand without changing performance of the outcome function. The bigger the hardness value, the bigger the disturbance required to produce change in behavior of the system."
2. Elasticity, or the amount of disturbance that a system can withstand without changing to a different steady state, that is, the amount of disturbance that a system can tolerate after bending from its reference behavior before never returning to it (before breaking). The bigger the elasticity value, the bigger the disturbance required to produce a new steady state.

We ran Monte Carlo analyses and varied rainfall minimums around average rainfall projections from climate models to change the uniform random distribution of rainfall variability, the magnitude of net migration rate and additional investment in hydropower to assess disturbance from new dams that may be built in the MFF after the Stung Treng dam. We then calculated the percentage deviation of our risk indicators from their reference value (the value produced by the baseline simulations) for each of 200 Monte Carlo runs. After ordering the simulation runs by size of disturbance, the maximum disturbance that the risk indicators could tolerate before (1) deviating significantly (at 5% confidence bound) from the baseline behavior (hardness) or (2) transforming so that the indicator behavior never returns to baseline behavior after the disturbance (elasticity) was manually identified. We performed this resilience analysis for several indicators that reflect the different priorities different stakeholder groups have for nexus development. We refrained from an overall resilience assessment because that would have implied assigning weights to each of these priorities.

## RESULTS

### Stakeholder priorities and anticipated risks in the Mekong Flooded Forest Landscape

Poverty was consistently identified as a major threat, and poverty reduction as the most important priority, across individual stakeholders and stakeholder groups in all CLD procedures. Generally speaking, agriculture and fisheries management are seen as important development pathways for the provinces (CA2015_6), though participants were highly pessimistic about the state of local fisheries and concerned about water availability

**Table 3**. Risk indicators for Kratie and Stung Treng provinces in the Mekong Flooded ForestLandscape (MFF). NSDP, National Strategic Development Plan.

| Summary of stakeholder priorities during causal loop diagram (CLD) procedures and discussions | Analyst-selected indicators in the MFF model for the scenario and resilience analyses |
|---|---|
| Poverty reduction is a national and provincial sustainable development priority, interpreted in this analysis as acting on vulnerability reduction (Aggregated CLD, NSDP 2008–2013, 2014–2018). | Per capita income, indicated in absolute values of USD/person/year. This is GDP per person, aggregated across all people living in the two provinces and not disaggregated by type of job and salary. |
| Illegal fishing in the context of the current degraded state of fish stocks (before dam construction) was identified as a threat to livelihoods and food security in multiple stakeholder workshops (MSC1,3,4; SF5.1_2017.03.13. Notes from prov&farmers trainingST.docx). | Crop self-sufficiency and fish self-sufficiency, indicated as a percentage of food demand (t/year) compared to domestic food supply, where "domestic" refers to Kratie and Stung Treng provinces. Production is disaggregated by crops (t/year) and fish (t/year). Considering both crop self-sufficiency and fish self-sufficiency sheds light on overall food availability, farming and fishing livelihoods, and nutrition quality (e.g., Orr et al. 2012). |
| Drought conditions prevailed in the three years previous to the project and water availability was highlighted as a relatively new challenge for human and animal populations in the landscape.(SF2.1_2016.07.20summary). | Relative water consumption, annual water consumption in L/year to water consumption in the year 2000, the initial year for the model simulations. This measure is indicative only. As a result of the data-poor environment we are operating in, this indicator measures only direct water consumption and not the wider changes in hydrological flows that result from hydropower development (e.g., Dang et al. 2016). It is important to keep this model boundary in mind when interpreting model results. |
| Local energy access from renewable sources is a national sustainable development priority because it is assumed that increasing renewable energy access will stimulate economic development, reducing poverty and vulnerability of local populations while addressing climate change. (RGC 2008, 2014, 2016*d*.) | Energy self-sufficiency, indicated as a percentage of energy demand (MWh/year) compared to domestic energy supply (MWh/year), where "domestic" refers to Kratie and Stung Treng provinces. Positive welfare impacts from energy access are assumed based on regional data (Khandker et al. 2013). |

for agricultural activities into the future. Table 3 displays priorities for Kratie and Stung Treng stakeholders and associated indicators within the MFF model selected by the research analysts for the scenario and resilience analyses.

Our simulation modeling focuses on how these indicators perform. Our analysis confirms some expected trade-offs between national-level energy security and economic growth and MFF food, livelihoods, and water security, while also revealing a new understanding of some drivers of these outcomes. We report the most surprising results and the nuances generated by the dynamic modeling in reporting the scenario and resilience modeling outputs.

### Scenario analysis results

Scenario results are shown in two different forms in Figure 3: graph (a) displays the time-dependent values of the absolute indicator values while graph (b) compares the scenarios—baseline with Stung Treng dam, adaptation (dam + higher rice yields), and mitigation (dam + E-flows)—to the behavior of our reference scenario, the "baseline without dam."

Negative effects on crop self-sufficiency (Fig. 3a) are not as strong as might be expected given dam impacts on water and land availability. The main reason is an assumption made in the model that further agricultural land will be available for cultivation if crop production productivity reduces in the future because of reduced extent of seasonal inundation.

Reduced sediment flows are assumed to lower availability of organic sources of nutrients to agricultural activities. Because of lack of affordability, all nutrients required to maintain productivity cannot be provided by additional mineral fertilizer purchases and thus, more agriculture land will be sought. Forest land is the main land type converted, which would lead to a decline in a variety of ecosystem services that are hard to quantify.

In the alternative crops scenario, agricultural productivity increases substantially on existing agricultural land, which reduces the pressure to convert forest land. Introducing higher rice yields leads to some improvements but these fade over time (cf. convergence between the lines for "base with dam" and "dam + alternative crops" in Fig. 3.1b). Crop production is similar across these scenarios because forest land to agricultural cultivation in "base with dam" scenario produces similar production effects as higher rice yields being sought on existing agricultural land.

The introduction of high environmental flow requirements (e-flows) has the largest mitigating impact on crop self-sufficiency risks. The main driver behind these differences is the assumed nutrient availability for crop growth embodied in flow sediments. Higher e-flows also mitigate some of the negative impacts of the hydropower dam on fish self-sufficiency (Fig 3.2a). This mitigation scenario also results in higher energy self-sufficiency than observed in the "base without dam" scenario. Interestingly, this scenario improves per capita income compared to the other scenarios including the dam. This is due a combination of two processes: (1) an increase in crop production and (b) a more stable generation of hydropower with its subsequent beneficial impacts on economic activities at large. The planned hydropower expansion leads to improvement in local energy self-sufficiency only under an assumption that at least 15% of the new power capacity is allocated for local use (Fig. 3a and b).

A principal point is that model results indicate some trade-offs in crop self-sufficiency, fish self-sufficiency, and energy self-sufficiency in all scenarios, and not just those with dam development. Water consumption (relative to the year 2000) also increases in all scenarios, but somewhat less where agricultural production is restrained because land availability reduces after dam development. Per capita income increases in the short run

**Fig. 3**. Risk indicator outcomes for the different scenarios.

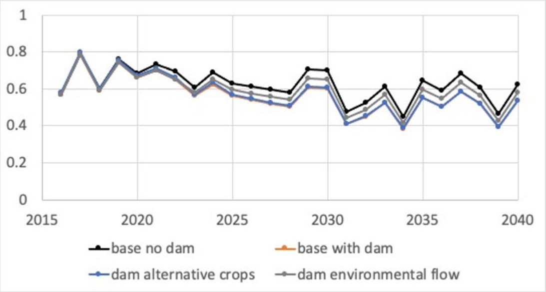
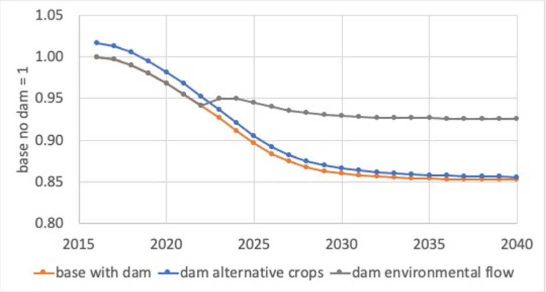
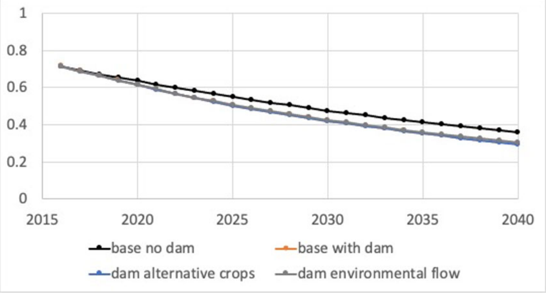
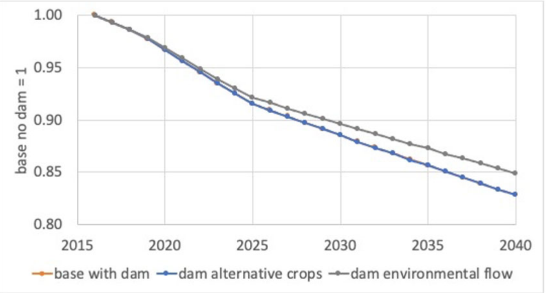
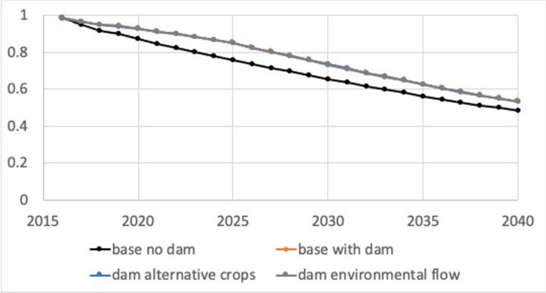
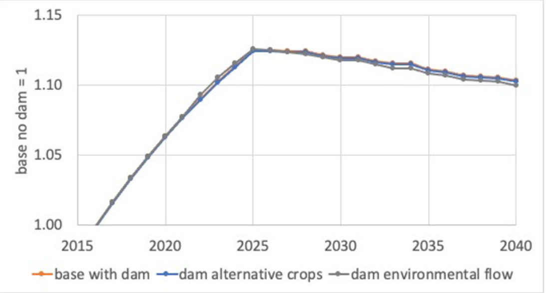
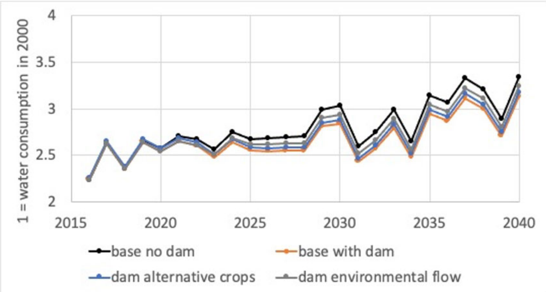
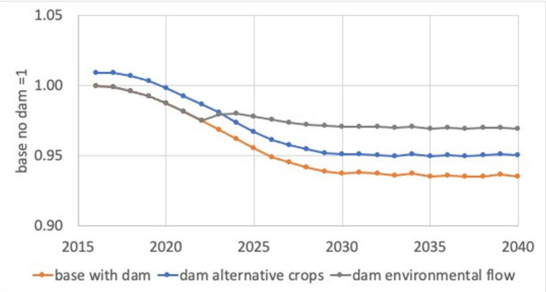
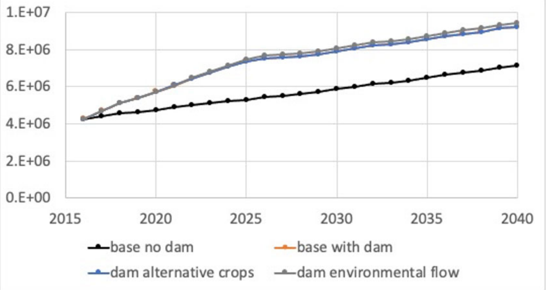
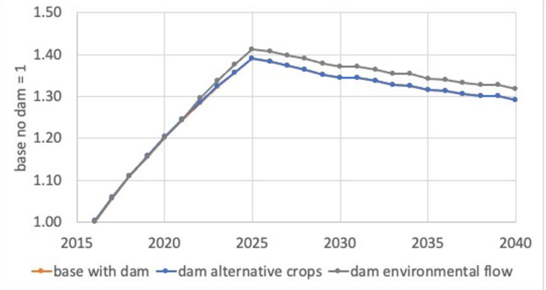
| | a) Absolute outcomes | a) Outcomes relative to Scenario 1 – Baseline trends (without dams) |
|---|---|---|
| 1. Crop self sufficiency |  |  |
| 2. Fish self sufficiency |  |  |
| 3. Energy self sufficiency |  |  |
| 4. Relative water consumption |  |  |
| 5. Per capita income |  |  |

**Table 4**. Resilience of risk indicators to climate change at 5% confidence bound.

| | Crop self-sufficiency | Fish self-sufficiency | Energy self-sufficiency | Relative water consumption | Per capita income |
|---|---|---|---|---|---|
| Hardness, % disturbance | | | | | |
| Base no dam | 6.3% | Null value | 90.4% | 16.9% | 50.8% |
| Base with dam | 6.3% | Null value | 63.2% | 14.8% | 47.5% |
| Dam with alternative crops | 6.3% | Null value | 63.2% | 14.8% | 47.5% |
| Dam environmental flow | 6.3% | Null value | 64.9% | 14.8% | 49.3% |
| Elasticity, % disturbance | | | | | |
| Base no dam | 85.7% | Null value | 91.6% | 48.0% | 64.9% |
| Base with dam | 43.2% | Null value | 90.4% | 57.5% | 56.4% |
| Dam with alternative crops | 25.2% | Null value | 85.1% | 54.3% | 63.2% |
| Dam environmental flow | 25.2% | Null value | 84.1% | 15.7% | 63.2% |

for all scenarios with the construction of the Stung Treng dam because stakeholders assume local employment increases as the dam is constructed. The growth rate drops as soon as dam construction is completed however. Furthermore, after dam construction, the minor gains in additional income from an increase in economic productivity suggested by the model is somewhat dampened by a 15% reduction in the value of food production in the "base with dam" and "dam alternative crops" scenarios.

### Resilience analysis results

For climate change (Table 4), a low hardness value of 6.3 for crop self-sufficiency in the "base no dam" indicates that a reduction in the rainfall minimum by just 6.3% leads to significantly different values in crop self-sufficiency, even with no dam developments. One of the most significant findings is that while the introduction of the hydropower dam does not seem to have a fundamental impact on crop self-sufficiency in absolute terms (Fig. 3), it does reduce resilience of crop self-sufficiency to climate change even with mitigation or adaptation interventions. This becomes particularly evident when elasticity drops from around 86% to 43% for the dam scenario, and lower again with alternative cropping systems or e-flow standards (25%).

A second key result is the marked trade-off between income and energy self-sufficiency on the one hand and resilience for relative water consumption on the other hand with e-flow requirements (mitigation scenario). The elasticity of relative water consumption is considerably lower than in all other scenarios. Energy self-sufficiency resilience to climate change decreases in all scenarios with the dam, even assuming that some of the new power capacity created by the hydropower developments will be redirected to the local economy. The adaptation and mitigation scenarios increase the hardness of energy self-sufficiency compared to the baseline (with dam), but they decrease elasticity marginally. Fish self-sufficiency is not resilient at all to climate change. The absence of any hardness or elasticity values in the tables indicates that any disturbance beyond the reference value leads to a significant deviation from the reference runs without the indicators ever bouncing back to the reference values.

Crop self-sufficiency is not resilient to additional population growth (absence of hardness as well as elasticity values in Table 5). For our other indicators, a deviation between 7% and 9% from the reference assumptions is sufficient for the system to deviate from its reference behavior (hardness values). Table 5 does not show elasticity measures for population growth because once indicator values differed significantly from their reference values in the model, they never bounce back in the model runs. This is likely because of the path dependencies for local food supply, which is highly reliant on local environmental systems and productive capacities.

**Table 5**. Resilience of risk indicators to population growth at 5% confidence bound.

| hardness, % disturbance | Crop self-sufficiency | Fish self-sufficiency | Energy self-sufficiency | Relative water consumption | Per capita income |
|---|---|---|---|---|---|
| Base no dam | Null value | 8.3% | 8.6% | Null value | 7.2% |
| Base with dam | Null value | 8.3% | 8.7% | 9.2% | 7.2% |
| Dam with alternative crops | Null value | 8.3% | 8.7% | Null values | 7.2% |
| Dam environmental flow | Null value | 8.3% | 9.0% | Null value | 7.2% |

Additional investments in hydropower capacity, e.g., Sambor dam, have mixed resilience impacts (Table 6). On the one hand, they improve energy self-sufficiency and per capita income (Fig. 3) given model assumptions about local employment gains and energy contributions to the local economy. However, hardness values are missing for most indicators and there are no elasticity measures once additional dam investments are introduced in the model run. Once again, when indicator values deviate from their reference values, they never bounce back because the model can find no way of fully compensating the reductions in crop, fish, or energy self-sufficiency or per capita income introduced by additional dam investments over time. This finding supports recent research on ecological design options for Sambor dam (Wild et al. 2019). Fish self-sufficiency does not appear either, but for a somewhat different reason. This indicator does not deviate significantly from scenario runs because there is little local fish production left to impact by the time the additional dam investment would be made. Similarly, a hardness value of 33% indicates that it does not take much more than current hydropower dam investment before crop self-sufficiency deteriorates even more.

**Table 6**. Resilience of risk indicators to additional dam investments at 5% confidence bound.

| hardness, % disturbance | Crop self-sufficiency | Fish self-sufficiency | Energy self-sufficiency | Relative water consumption | Per capita income |
|---|---|---|---|---|---|
| Base no dam | Null value | Null values | Null value | Null values | Null value |
| Base with dam | 33.3% | Null value | Null value | 77.0% | Null value |
| Dam with alternative crops | 33.3% | Null value | Null value | 77.0% | Null value |
| Dam environmental flow | 33.3% | Null value | Null value | 77.0% | Null value |

## DISCUSSION

Our aim here is to give insight into some advantages and disadvantages of our methodology. We note upfront that we cannot compare directly to other methods given unique contextual factors for our study. Instead, we reflect on the modeling process and outputs in the frame of our original intended objectives: to elicit and integrate knowledge from diverse stakeholders, assess direct and indirect, short- and long-term risks and consequences in the nexus situation in our Cambodia case and enhance agency for individuals and collectives who participated.

We did not depend on expert-led risk identification or enter through the nexus silos of water, energy, or food. Taking this systems perspective helped stakeholders share their own priority concerns, vulnerabilities, and knowledge in our process. The participatory CLDs surfaced unshared information and unaired assumptions, and this knowledge was reflected in the aggregated CLD and model structure (see Appendix 2 for further details). Because of this we gained a new understanding about how local communities are already trying to cope with severely degraded fish stocks even before hydropower development, for example. One local civil society partner remarked: “I myself learned that village people are really more concerned about illegal fishing. Their second priority is the [future] dam development. The illegal fishing is actually happening” (MSC3). Ideas and viewpoints that are not often raised were deliberated and negotiated in some groups where barriers to speaking across hierarchy were weakened, at least temporarily (see Bréthaut et al. 2019). Being able to talk about hydropower impacts with this mix of stakeholders was viewed as unusual and a successful outcome of the participatory modeling method by some project partners (MSC7) given political conditions.

The resulting scenario and resilience analysis produce some interesting insights for future risk governance in the landscape. They highlight how trade-offs between national energy infrastructure programs and local food security will likely be made in a situation where serious pressure is already being exerted on environmental systems in Kratie and Stung Treng provinces. This implies that although investing in fish management seems to be a robust strategy, it must be designed for conditions where dams are being developed on top of already degraded fish stocks. And, significantly, local food security problems could be triggered even by small increases in local population driven by construction activities, and not just by subsequent effects on fish production and other biodiversity of a completed and operational dam. Although climate change is a major concern for national government, Kratie and Stung Treng provinces may be more resilient to climate disturbances than to disturbances from population growth or additional dam investments.

Moreover, neither the adaptation or mitigation measures proposed by stakeholders can be relied on to fully compensate for loss in crop and fish self-sufficiency resulting from dam development under climate change conditions. This suggests giving weight to finding pathways to improved resilience outcomes. Two “no regrets” policy actions are worth further exploration in light of multiple and large uncertainties involved: (1) regenerating natural resources and strengthening local food production systems as a buffer. A focus on aquatic food production might be the best hedge for food security even with hydropower developments in the landscape, though this claim will have to be assessed against future increases in population and/or fishing effort; (2) requiring e-flow measures to be implemented by dam project developers with assessments of future possible water demand in the landscape. Effectiveness of e-flow measures will depend greatly on coordinated operational rules along the cascade of dams in the region and should not be expected to offset impacts completely. Our analysis suggests very careful consideration of assumptions related to three key variables in future research and governance actions in the MFF nexus:

- Costs associated with increasing land-based food production. These need to include opportunity costs of expanding land under cultivation when we understand that this implies converting forest land, additional costs for farmers for increased fertilizer and plant protection products, and other implementation costs for increasing crop production. In addition, future water availability must be evaluated, along with new, additional costs to local communities for drinking water and irrigation infrastructure, i.e., water pumps.
- Population in the two provinces. Population growth affects fish self-sufficiency in our model runs irrespective of whether we included the dam development, indicating that local food production is under significant pressure even before dams are built. This implies that even temporary inward migration of infrastructure construction workers or tourist numbers must be considered carefully in planning local food production and imports in this region.
- Direct economic benefits to local communities from dam construction employment or economic development opportunities enabled by increased access to energy. These are important assumptions in the analysis and if they do not hold, then outcomes for the risk indicators would change significantly, particularly given that so much local economic activity depends on natural resources provisioning, biodiversity, and scenic values of local ecosystems.

The limitation of our analysis is that it stops at identifying the data essential to a full policy analysis and suggesting important factors to be understood before coming to policy conclusions. Nonetheless, stakeholder reflections on the scenario modeling results during final landscape and national-level workshops indicated that the procedure had helped develop provincial administration capacity for nexus analysis and governance. In a closing speech to the final provincial-level workshop, a senior provincial administration official reflected that, "The use of this information is easy because these findings have been obtained by all of you. We cannot take a U.S. study and adopt it here. Starting from the bottom up approach is easy ... because we can coordinate ... This study for all of us is unique. It brings to us the vision, one common vision for us. We can use it as a compass" (SF2.1_2016.07.19-20).

Interestingly, it was the developing planning processes that emerged as the most promising nexus governance opportunity by the end of our research process, not the expected sectoral nexus policy areas of water, energy, agricultural, and fisheries production. The Ministry of Interior D&D process is generating new guidelines for subnational development planning across Cambodia in the context of nation-wide development planning procedures, which in turn influence national sectoral strategies, like agriculture and fisheries management, climate action, and energy production. A number of partners and participants observed that current problem identification procedures in commune investment planning (typically SWOT analysis) is unhelpful because it generates narrow risk and priority assessments and actions (MSC1) compared to more holistic and integrated analysis enabled by the CLD process (MSC3). We initially provided training in the CLD method to our academic, civil society, and national government operational partners to be able to facilitate workshops in the Khmer language. After the project, the NCSD secretariat staff, WWF staff, RUPP and RUA academics all cited increases in their confidence and ability to facilitate basic CLD activities and train others to do the same (MSC3). Some key Ministry of Interior staff also showed interest in taking up the CLD methodology also, with one project partner reporting, "NCDD focal points in provincial administrations for the NCDD are really interested. They have already spent time to discuss where the tool could fit into the subnational development planning processes. I believe the NCDD could take up this this tool because they are currently in the process of updating their toolkit for commune investment planning. I have already received a call to invite me to present the CLD process at such an event." (MSC4). Provincial administration staff were also interested in continuing with the CLD method but wanted to see the process formally integrated into national planning guidelines produced by the Ministry of Interior first (MSC12; see Bréthaut et al. 2019 for further details).

This outcome suggests something important for future applications of similar research and analysis methods. Originally, we anticipated that any new capacity for risk identification and management reported by partners would likely derive from new knowledge produced by the modeling analysis. In effect, we underestimated the impact of the CLD training provided to operational partners and the value derived by the participants from the CLD procedures themselves. We took up measurement of changed mental models (Scott et al. 2016) and enhanced agency for individuals and collectives in participatory system dynamics modeling in Kimmich et al. (2019) to study this question experimentally. Our findings reveal how participants in such processes can significantly change beliefs about likelihood of certain future events and their individual agency to manage these, while reducing some uncertainties within and across the groups about priority actions.

## CONCLUSION

We share findings from the LIVES project on the use of one procedure for identifying key risks in one water-energy-food nexus case in the Mekong region. A motivating idea was that assessments should be carried out with stakeholders if such assessments are to support equitable risk allocation in situations of information asymmetries, low consensus on priorities and problems, and varying vulnerabilities and capacities.

Our chosen method was participatory system dynamics modeling with scenario and resilience analysis. Such models have been referred to as being theory-rich and data-poor (Pruyt 2014). We find this may be a strength of this method when it obliges nexus researchers to turn to local stakeholders as an important source of knowledge. Scenario analysis depends on so many empirical and structural modeling assumptions that always have to be made. In our case, we attempted to make these with stakeholders in a cocreated evaluative process with the result that risks are defined by those who might face them, and everyone's assumptions and proffered responses are tested and validated by a collective process.

A lesson from our experience that reinforces the conclusions of other transdisciplinary research is that nexus research does not have to produce perfect data and incontestable results before helping to anticipate and identify responses to risks in the nexus. This case shows it is possible to use complex modeling approaches for stakeholder-led analyses. The process was time consuming for all involved, longer and more uncertain compared to more conventional approaches. However, stakeholders had an unexpected appetite for systems thinking precisely because they found it helpful in navigating the complexity of their situation. Participatory system dynamics models are currently underutilized in nexus research (Albrecht et al. 2018, Harwood 2018) but absolutely deserve further attention because of the opportunities for inclusion, deliberation, and learning they offer to nexus governance.

Finally, working with stakeholders and our analytical procedure underscored for us how nexus risk assessments change with changes in perspective. In light of this, we believe a tentative characterization of risk in the water-energy-food nexus will be helpful to future efforts in participatory modeling for such assessments. Risk intensification or transfer due to nexus relations is the probability and severity of consequences arising from rapidly changing framework conditions in systems affected by the dynamic interconnections between water, energy, and food production subsystems which, in turn, affect (1) hazard likelihood, exposure, and vulnerability (2) for multiple stakeholders (3) with varying adaptive capacities that have (4) different sensitivities to interventions (5) across scales. Even if ability to implement systems-thinking procedures is impaired, bearing in mind such characteristics supports a precautionary and multilevel approach in risk assessment for the nexus where social-ecological resilience is thought to be low.

*Responses to this article can be read online at:*
https://www.ecologyandsociety.org/issues/responses.php/11919

---

**Acknowledgments:**

*We gratefully acknowledge funding support of the Nomis Foundation and the Mava Foundation. This research was undertaken as part of the Linked Indicators for Vital Ecosystem Services project (http://livesproject21.org/). Thank you to all participants and partners in our Cambodia activities. This article reflects the findings of the research but does not necessarily reflect the views of the institutions with which authors are affiliated.*

**Data Availability:**

*The data that support the findings of this study are available on request from the corresponding author, [LG]. The data/code are not publicly available because they contain information that could compromise the privacy of research participants.*

---

## LITERATURE CITED

Al-Saidi, M., and N. A. Elagib. 2017. Towards understanding the integrative approach of the water, energy and food nexus. *Science of The Total Environment* 574:1131-1139. https://doi.org/10.1016/j.scitotenv.2016.09.046

Albrecht, T. R., A. Crootof, and C. A. Scott. 2018. The water-energy-food nexus: a systematic review of methods for nexus assessment. *Environmental Research Letters* 13(4):043002. https://doi.org/10.1088/1748-9326/aaa9c6

Babel, M. S., C. Nguyen Dinh, Md. Reaz Akter Mullick, and U. V. Nanduri. 2012. Operation of a hydropower system considering environmental flow requirements: a case study in La Nga River Basin, Vietnam. *Journal of Hydro-Environment Research* 6 (1):63-73. https://doi.org/10.1016/j.jher.2011.05.006

Barlas, Y. 1996. Formal aspects of model validity and validation in system dynamics. *System Dynamics Review* 12(3):183-210. https://doi.org/10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4

Basco-Carrera, L., A. Warren, E. van Beek, A. Jonoski, and A. Giardino. 2017. Collaborative modelling or participatory modelling? A framework for water resources management. *Environmental Modeling & Software* 91(Supplement C):95-110. https://doi.org/10.1016/j.envsoft.2017.01.014

Bassi, A., L. Gallagher, and H. Helsingen. 2016. Green economy modelling of ecosystem services along the "Road to Dawei." *Environments* 3(4):19. https://doi.org/10.3390/environments3030019

Bouckaert, F., Y. Wei, K. Hussey, J. Pittock, and R. Ison. 2018. Improving the role of river basin organisations in sustainable river basin governance by linking social institutional capacity and basin biophysical capacity. *Current Opinion in Environmental Sustainability* 33:70-79. https://doi.org/10.1016/j.cosust.2018.04.015

Boyd, E., B. Nykvist, S. Borgström, and I. A. Stacewicz. 2015. Anticipatory governance for social-ecological resilience. *Ambio* 44(1):149-161. https://doi.org/10.1007/s13280-014-0604-x

Bréthaut, C., L. Gallagher, J. Dalton, and J. Allouche. 2019. Power dynamics and integration in the water-energy-food nexus: learning lessons for transdisciplinary research in Cambodia. *Environmental Science & Policy* 94:153-162. https://doi.org/10.1016/j.envsci.2019.01.010

Bylander, M. 2015. Depending on the sky: environmental distress, migration, and coping in rural Cambodia. *International Migration* 53(5):135-147. https://doi.org/10.1111/imig.12087

Chapman, A., and S. Darby. 2016. Evaluating sustainable adaptation strategies for vulnerable mega-deltas using system dynamics modeling: rice agriculture in the Mekong Delta's An Giang Province, Vietnam. *Science of The Total Environment* 559:326-338. https://doi.org/10.1016/j.scitotenv.2016.02.162

Clark, W. C., L. van Kerkhoff, L. Lebel, and G. C. Gallopin. 2016. Crafting usable knowledge for sustainable development. *Proceedings of the National Academy of Sciences* 113 (17):4570-4578. https://doi.org/10.1073/pnas.1601266113

Dang, T. D., T. A. Cochrane, M. E. Arias, P. D. T. Van, and T. T. de Vries. 2016. Hydrological alterations from water infrastructure development in the Mekong floodplains. *Hydrological Processes* 30(21):3824-3838. https://doi.org/10.1002/hyp.10894

Dart, J., and R. Davies. 2003. A dialogical, story-based evaluation tool: the most significant change technique. *American Journal of Evaluation* 24(2):137-155. https://doi.org/10.1177/109821400302400202

Foran, T. 2015. Node and regime: interdisciplinary analysis of water-energy-food nexus in the Mekong region. *Water Alternatives* 8(1):655-674. [online] URL: http://www.water-alternatives.org/index.php/alldoc/articles/vol8/v8issue1/270-a8-1-3/file

Foran, T., J. Ward, E. J. Kemp-Benedict, and A. Smajgl. 2013. Developing detailed foresight narratives: a participatory technique from the Mekong region. *Ecology and Society* 18(4):6. https://doi.org/10.5751/ES-05796-180406

Forrester, J. W. 1961. *Industrial dynamics.* Productivity Press, Portland, Oregon, USA.

Fox, C., and C. Sneddon. 2019. Political borders, epistemological boundaries, and contested knowledges: constructing dams and narratives in the Mekong River basin. *Water* 11(3):413. https://doi.org/10.3390/w11030413

Gallagher, L., J. Dalton, C. Bréthaut, T. Allan, H. Bellfield, D. Crilly, K. Cross, D. Gyawali, D. Klein, S. Laine, X. LeFlaive, L. Li, A. Lipponen, N. Matthews, S. Orr, J. Pittock, C. Ringler, M. Smith, D. Tickner, U. von Schlippenbach, and F. Vuille. 2016. The critical role of risk in setting directions for water, food and energy policy and research. *Current Opinion in Environmental Sustainability* 23:12-16. https://doi.org/10.1016/j.cosust.2016.10.002

Gerritsen, A. L., M. Stuiver, and C. J. A. M Termeer. 2013. Knowledge governance: an exploration of principles, impact, and barriers. *Science and Public Policy* 40(5):604-615. https://doi.org/10.1093/scipol/sct012

Ghaffarzadegan, N., J. Lyneis, and G. P. Richardson. 2010. How small system dynamics models can help the public policy process. *System Dynamics Review* 27(1):22-44. https://doi.org/10.1002/sdr.442

Grafton, R. Q., M. McLindin, K. Hussey, P. Wyrwoll, D. Wichelns, C. Ringler, D. Garrick J. Pittock, S. Wheeler, S. Orr, N. Matthews, E. Ansink, A. Aureli, D. Connell, L. De Stefano, K. Dowsley, S. Farolfi, J. Hall, P. Katic, B. Lankford, H. Leckie, M. McCartney, H. Pohlner, N. Ratna, M. H. Rubarenzya, S. Narayan Sai Raman, K. Wheeler, and J. Williams. 2016. Responding to global challenges in food, energy, environment and water: risks and options assessment for decision-making. *Asia & the Pacific Policy Studies* 3(2):275-299. https://doi.org/10.1002/app5.128

Guston, D. H. 2014. Understanding "anticipatory governance." *Social Studies of Science* 44(2):218-242. https://doi.org/10.1177/0306312713508669

Hagemann, N., and S. Kirschke. 2017. Key issues of interdisciplinary nexus governance analysis: lessons learned from research on integrated water resources management. *Resources* 6 (1):9. https://doi.org/10.3390/resources6010009

Haimes, Y. Y. 2009. On the complex definition of risk: a systems-based approach. *Risk Analysis* 29(12):1647-1654. https://doi.org/10.1111/j.1539-6924.2009.01310.x

Harwood, S. A. 2018. In search of a (WEF) nexus approach. *Environmental Science & Policy* 83:79-85. https://doi.org/10.1016/j.envsci.2018.01.020

Herrera, H. 2017. From metaphor to practice: operationalizing the analysis of resilience using system dynamics modeling. *Systems Research and Behavioral Science* 34(4):444-462. https://doi.org/10.1002/sres.2468

Hoff, H. 2011. *Understanding the nexus. Background paper for the Bonn2011 conference: the water, energy and food security nexus.* Stockholm Environment Institute, Stockholm, Sweden. [online] URL: https://www.sei.org/publications/understanding-the-nexus/.

Hovmand, P. S., D. F. Andersen, E. Rouwette, G. P. Richardson, K. Rux, and A. Calhoun. 2012. Group model-building 'scripts' as a collaborative planning tool. *Systems Research and Behavioral Science* 29(2):179-193. https://doi.org/10.1002/sres.2105

Howarth, C., and I. Monasterolo. 2017. Opportunities for knowledge co-production across the energy-food-water nexus: making interdisciplinary approaches work for better climate decision making. *Environmental Science & Policy* 75:103-110. https://doi.org/10.1016/j.envsci.2017.05.019

Innes, J. E., and D. E. Booher. 2010. *Planning with complexity: an introduction to collaborative rationality for public policy*. Routledge, London, UK. https://doi.org/10.4324/9780203864302

International Renewable Energy Agency (IRENA). 2018. *Renewable energy market analysis: Southeast Asia.* IRENA, Abu Dhabi, UAE. [online] URL: https://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_Market_Southeast_Asia_2018.pdf

Johnston, R., J. Cools, S. Liersch, S. Morardet, C. Murgue, M. Mahieu, I. Zsuffa, and G. P. Uyttendaele. 2013. WETwin: a structured approach to evaluating wetland management options in data-poor contexts. *Environmental Science and Policy* 34:3-17. https://doi.org/10.1016/j.envsci.2012.12.006

Jordan, R., S. Gray, M. Zellner, P. D. Glynn, A. Voinov, B. Hedelin, E. J. Sterling, K. Leong, L. Schmitt Olabisi, K. Hubacek, P. Bommel, T. K. BenDor, A. J. Jetter, B. Laursen, A. Singer, P. J. Giabbanelli, N. Kolagani L. Basco Carrera, K. Jenni, and C. Prell. 2018. Twelve questions for the participatory modeling community. *Earth's Future* 6(8):1046-1057. https://doi.org/10.1029/2018EF000841

Khandker, R. S., D. F. Barnes, and H. A. Samad. 2013. Welfare impacts of rural electrification: a panel data analysis from Vietnam. *Economic Development and Cultural Change* 61 (3):659-692. https://doi.org/10.1086/669262

Kimmich, C., L. Gallagher, B. Kopainsky, M. Dubois, C. Sovann, C. Buth, and C. Bréthaut. 2019. Participatory modeling updates expectations for individuals and groups, catalyzing behavior change and collective action in water-energy-food nexus governance. *Earth's Future* 7(12):1337-1352. [online] URL: https://doi.org/10.1029/2019EF001311

Klinke, A., and O. Renn. 2012. Adaptive and integrative governance on risk and uncertainty. *Journal of Risk Research* 15 (3):273-292. https://doi.org/10.1080/13669877.2011.636838

Kopainsky, B., G. Hager, H. Herrera, and P. H. Nyanga. 2017. Transforming food systems at local levels: using participatory system dynamics in an interactive manner to refine small-scale farmers' mental models. *Ecological Modeling* 362:101-110. https://doi.org/10.1016/j.ecolmodel.2017.08.010

Lang, D. J., A., Wiek, M., Bergmann, M. Stauffacher, P. Martens, P. Moll, M. Swilling, and C. J. Thomas. 2012. Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability Science* 7(1):25-43. https://doi.org/10.1007/s11625-011-0149-x

Larcom, S., and T. van Gevelt. 2017. Regulating the water-energy-food nexus: interdependencies, transaction costs and procedural justice. *Environmental Science and Policy* 72:55-64. https://doi.org/10.1016/j.envsci.2017.03.003

Lebel, L., and B. Lebel. 2018. Nexus narratives and resource insecurities in the Mekong region. *Environmental Science & Policy* 90:164-172. https://doi.org/10.1016/j.envsci.2017.08.015

Luna-Reyes, L. F., I. J. Martinez-Moyano, T. A. Pardo, A. M. Cresswell, D. F. Andersen, and G. P. Richardson. 2006. Anatomy of a group model-building intervention: building dynamic theory from case study research. *System Dynamics Review* 22(4):291-320. https://doi.org/10.1002/sdr.349

Ly, P., L. S. Jensen, T. B. Bruun, and A. de Neergaard. 2016. Factors explaining variability in rice yields in a rain-fed lowland rice ecosystem in southern Cambodia. *NJAS - Wageningen Journal of Life Sciences* 78:129-137. https://doi.org/10.1016/j.njas.2016.05.003

Ly, P., L. S. Jensen, T. B. Bruun, D. Rutz, and A. de Neergaard. 2012. The system of rice intensification: adapted practices, reported outcomes and their relevance in Cambodia. *Agricultural Systems* 113:16-27. https://doi.org/10.1016/j.agsy.2012.07.005

Mekong River Commission (MRC). 2017. *The study on the sustainable management and development of the Mekong River Basin, including impacts of mainstream hydropower projects*. MRC, Vientiane, Laos. [online] URL: http://www.mrcmekong.org/assets/Publications/Council-Study/Council-study-Reports-discipline/Council-Study-BioRA-Final-Technical-Report-VOLUME-4-Development-Scenarios-FINAL-REPORT-DEC-2017.pdf

Mekong Wetlands Biodiversity Conservation and Sustainable Use Programme. 2005. *Vulnerability assessment of Climate Risks in Stung Treng Province, Cambodia*. UNDP, MRC, GEF, IUCN, Gland, Switzerland. [online] URL: https://www.iucn.org/content/vulnerability-assessment-climate-risks-stung-treng-province-cambodia

Middleton, C., N. Matthews, and N. Mirumachi. 2015. Whose risky business? Public-private partnerships (PPP), build-operate-transfer (BOT) and large hydropower dams in the Mekong region. Pages 224-237 *in* N. Matthews and K. Geheb, editors. *Hydropower development in the Mekong region: political, socio-economic and environmental perspectives* Earthscan, London, UK.

Milne, S., and S. Mahanty, editors. 2015. *Conservation and development in Cambodia: exploring frontiers of change in nature, state and society*. Routledge, London, UK. https://doi.org/10.4324/9781315887302

Mochizuki, J., S. Vitoontus, B. Wickramarachchi, S. Hochrainer-Stigler, K. Williges, R. Mechler, and R. Sovann. 2015. Operationalizing iterative risk management under limited information: fiscal and economic risks due to natural disasters in Cambodia. *International Journal of Disaster Risk Science* 6 (4):321-334. https://doi.org/10.1007/s13753-015-0069-y

Molle, F., T. Foran, and M. Käkönen, editors. 2012. *Contested waterscapes in the Mekong Region: hydropower, livelihoods and governance.* Routledge, London, UK. https://doi.org/10.4324/9781849770866

Orr, S., J. Pittock, A. Chapagain, and D. Dumaresq. 2012. Dams on the Mekong River: lost fish protein and the implications for land and water resources. *Global Environmental Change* 22 (4):925-932. https://doi.org/10.1016/j.gloenvcha.2012.06.002

Pahl-Wostl, C. 2019. The role of governance modes and meta-governance in the transformation towards sustainable water governance. *Environmental Science and Policy* 91:6-16. https://doi.org/10.1016/j.envsci.2018.10.008

Parkhurst, J. 2016. Appeals to evidence for the resolution of wicked problems: the origins and mechanisms of evidentiary bias. *Policy Sciences* 49(4):373-393. https://doi.org/10.1007/s11077-016-9263-z

Pittock, J., D. Dumaresq, and A. M. Bassi. 2016. Modeling the hydropower-food nexus in large river basins: a Mekong case study. *Water* 8:425. https://doi.org/10.3390/w8100425

Poff, N. L., and J. H. Matthews. 2013. Environmental flows in the Anthropocene: past progress and future prospects. *Current Opinion in Environmental Sustainability* 5(6):667-675. https://doi.org/10.1016/j.cosust.2013.11.006

Pohl, C., S. Rist, A. Zimmermann, P. Fry, G. S. Gurung, F. Schneider, C. Ifejika Speranza, B. Kiteme, S. Boillat, E. Serrano, G. Hirsch Hadorn, and U. Wiesmann. 2010. Researchers' roles in knowledge co-production: experience from sustainability research in Kenya, Switzerland, Bolivia and Nepal. *Science and Public Policy* 37(4):267-281. https://doi.org/10.3152/030234210X496628

Pruyt, E. 2014. From data-poor to data-rich. System dynamics in the era of big data. *Paper presented at the 32nd International Conference of the System Dynamics Society*, 20-24 July. Delft, The Netherlands. [online] URL: https://proceedings.systemdynamics.org/2014/proceed/papers/P1390.pdf

Ratcliffe, R. 2020. Cambodia scraps plans for Mekong hydropower dams. *The Guardian,* 20 March. [online] URL: https://www.theguardian.com/world/2020/mar/20/cambodia-scraps-plans-for-mekong-hydropower-dams

Richter, B. D., and G. A. Thomas. 2007. Restoring environmental flows by modifying dam operations. *Ecology and Society* 12(1):12. https://doi.org/10.5751/ES-02014-120112

Rijke, J., R. Brown, C. Zevenbergen, R. Ashley, M. Farrelly, P. Morison, and S. van Herk. 2012. Fit-for-purpose governance: a framework to make adaptive governance operational. *Environmental Science & Policy* 22:73-84. https://doi.org/10.1016/j.envsci.2012.06.010

Rouwette, E. A. J. A. 2016. The impact of group model building on behavior. Pages 213-241 *in* M. Kunc, J. Malpass, and L. White, editors. *Behavioral operational research: theory, methodology and practice.* Palgrave Macmillan, London, UK. https://doi.org/10.1057/978-1-137-53551-1_11

Royal Government of Cambodia (RGC). 2008. *The Rectangular Strategy for Growth, Employment, Equity, and Efficiency in Cambodia.* Ministry of Planning. RGC, Phnom Penh, Cambodia.

Royal Government of Cambodia (RGC). 2011*a*. *Kratie provincial development planning 2011-2015.* Kratie provincial administration unit, RGC, Kratie, Cambodia.

Royal Government of Cambodia (RGC). 2011*b*. *Stung Treng provincial development planning 2011-2015.* Stung Treng provincial administration unit, RGC, Stung Treng, Cambodia.

Royal Government of Cambodia (RGC). 2014. *National Strategic Development Plan 2014-2018.* Ministry of Planning. RGC, Phnom Penh, Cambodia.

Royal Government of Cambodia (RGC). 2016*a*. *DRAFT Cambodia Energy Sector Strategy.* Ministry of Industry, Mines and Energy. RGC, Phnom Penh, Cambodia.

Royal Government of Cambodia (RGC). 2016*b*. *Cambodia National Energy Statistics.* Ministry of Industry, Mines and Energy. RGC, Phnom Penh, Cambodia.

Royal Government of Cambodia (RGC). 2016*c*. *DRAFT Cambodia Power Development Plan.* Ministry of Industry, Mines and Energy. RGC, Phnom Penh, Cambodia.

Royal Government of Cambodia (RGC). 2016*d*. *National Climate Change Action Plan.* Ministry of Environment. RGC, Phnom Penh, Cambodia.

Scheffer, M., S. R. Carpenter, T. M. Lenton, J. Bascompte, W. Brock, V. Dakos, J. van de Koppel, I. A. van de Leemput, S. A.

Levin, E. H. van Nes, M. Pascual, and J. Vandermeer. 2012. Anticipating critical transitions. *Science* 338(6105):344-348. https://doi.org/10.1126/science.1225244

Schipanski, M. E., G. K. MacDonald, S. Rosenzweig, M. J. Chappell, E. M. Bennett, R. Bezner Kerr, J. Blesh, T. Crews, L. Drinkwater, J. G. Lundgren, and C. Schnarr. 2016. Realizing resilient food systems. *BioScience* 66(7):600-610. https://doi.org/10.1093/biosci/biw052

Scott, R., R. Y. Cavana, and D. Cameron. 2016. Mechanisms for understanding mental model change in group model building. *Systems Research and Behavioral Science* 33(1):100-118. https://doi.org/10.1002/sres.2303

Shannak, S., D. Mabrey, and M. Vittorio. 2018. Moving from theory to practice in the water-energy-food nexus: an evaluation of existing models and frameworks. *Water-Energy Nexus* 1 (1):17-25. https://doi.org/10.1016/j.wen.2018.04.001

Siciliano, G., F. Urban, S. Kim, and P. D. Lonn. 2015. Hydropower, social priorities and the rural-urban development divide: the case of large dams in Cambodia. *Energy Policy* 86:273-285. https://doi.org/10.1016/j.enpol.2015.07.009

Sithirith, M. 2016. Dams and state security: damming the 3S rivers as a threat to Cambodian state security. *Asia Pacific Viewpoint* 57 (1):60-75. https://doi.org/10.1111/apv.12108

Smajgl, A., and J. Ward. 2013. *The water-food-energy nexus in the Mekong region: assessing development strategies considering cross-sectoral and transboundary impacts*. Springer, New York, New York, USA. https://doi.org/10.1007/978-1-4614-6120-3

Smajgl, A., J. R. Ward, T. Foran, J. Dore, J. Ward, and S. Larson. 2015. Visions, beliefs, and transformation: exploring cross-sector and transboundary dynamics in the wider Mekong region. *Ecology and Society* 20(2):15. https://doi.org/10.5751/ES-07421-200215

Smajgl, A., J. Ward, and L. Pluschke. 2016. The water-food-energy nexus - realising a new paradigm. *Journal of Hydrology* 533:533-540. https://doi.org/10.1016/j.jhydrol.2015.12.033

Sterman, J. 2000. *Business dynamics: systems thinking and modeling for a complex world*. Irwin/McGraw-Hill, New York, New York, USA.

Thilakarathne, M., and V. Sridhar. 2017. Characterization of future drought conditions in the Lower Mekong river basin. *Weather and Climate Extremes* 17:47-58. https://doi.org/10.1016/j.wace.2017.07.004

Thomas, T. S., T. Ponlok, R. Bansok, T. De Lopez, C. Chiang, N. Phirun, and C. Chhun. 2013. *Cambodian agriculture: adaptation to climate change impact.* IFPRI Discussion Paper 01285. International Food Policy Research Institute, Washington D.C., USA [online] URL: https://reliefweb.int/sites/reliefweb.int/files/resources/Cambodian%20agriculture%20adaptation%20to%20climate%20change%20impact.pdf

Thompson, J. R., C. L. R. Laizé, A. J. Green, M. C. Acreman, and D. G. Kingston. 2014. Climate change uncertainty in environmental flows for the Mekong River. *Hydrological Sciences Journal* 59(3-4):935-954. [online] URL: https://doi.org/10.1080/02626667.2013.842074

UN FAOSTAT 2018. *Crops.* Food and Agriculture Organization of United Nations, Rome, Italy. [online] URL: http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor

Urban, F., G. Siciliano, K. Sour, P. D. Lonn, M. Tan-Mullins, and G. Mang. 2015. South-south technology transfer of low-carbon innovation: large Chinese hydropower dams in Cambodia. *Sustainable Development* 23(4):232-244. https://doi.org/10.1002/sd.1590

van der Voorn, T., J. Quist, C. Pahl-Wostl, and M. Haasnoot. 2017. Envisioning robust climate change adaptation futures for coastal regions: a comparative evaluation of cases in three continents. *Mitigation and Adaptation Strategies for Global Change* 22(3):519-546. https://doi.org/10.1007/s11027-015-9686-4

Videira, N., P. Antunes, R. Santos, and R. Lopes. 2010. A participatory modeling approach to support integrated sustainability assessment processes. *Systems Research and Behavioral Science* 27(4):446-460. https://doi.org/10.1002/sres.1041

Villamayor-Tomas, S., M. Avagyan, M. Firlus, G. Helbing, and M. Kabakova. 2016. Hydropower vs. fisheries conservation: a test of institutional design principles for common-pool resource management in the lower Mekong basin social-ecological system. *Ecology and Society* 21(1):3. https://doi.org/10.5751/es-08105-210103

Voinov, A., N. Kolagani, M. K. McCall, P. D. Glynn, M. E. Kragt, F. O. Ostermann, S. Pierce, and P. Ramu. 2016. Modeling with stakeholders - next generation. *Environmental Modelling & Software* 77:196-220. https://doi.org/10.1016/j.envsoft.2015.11.016

Vuković, D., and M. Babović. 2018. The trap of neo-patrimonialism: social accountability and good governance in Cambodia. *Asian Studies Review* 42(1):144-160. https://doi.org/10.1080/10357823.2017.1414773

Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society* 9(2):5. https://doi.org/10.5751/ES-00650-090205

Weber, E. U. 1997. The utility of measuring and modeling perceived risk. Pages 45-57 *in* A. A. J. Marley, editor. *Choice, decision, and measurement: essays in honor of R. Duncan Luce*. First edition. Psychology Press, Routledge, New York, USA. https://doi.org/10.4324/9781315789408-4

Weitz, N., C. Strambo, E. Kemp-Benedict, and M. Nilsson. 2017. Closing the governance gaps in the water-energy-food nexus: insights from integrative governance. *Global Environmental Change* 45:165-173. https://doi.org/10.1016/j.gloenvcha.2017.06.006

Wild, T. B., P. M. Reed, D. P. Loucks, M. Mallen-Cooper, and E. D. Jensen. 2019. Balancing hydropower development and ecological impacts in the Mekong: tradeoffs for Sambor mega dam. *Journal of Water Resources Planning and Management* 145 (2):05018019. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001036

World Bank and The Asia Foundation. 2013. *Voice, choice and decision: a study of local governance processes in Cambodia*. World Bank, Washington, D.C., USA. [online] URL: https://openknowledge.worldbank.org/handle/10986/16758

Wu, S., H. Ishidaira, and W. Sun. 2010. Potential impact of Sambor dam project on interaction between Mekong river and Tonle Sap lake. *Annual Journal of Hydraulic Engineering* 54:109-114. [online] URL: http://library.jsce.or.jp/jsce/open/00028/2010/54-0019.pdf

Yung, L., E. Louder, L. Gallagher, K. Jones, and C. Wyborn. 2019. How methods for navigating uncertainty connect science and policy at the water-energy-food nexus. *Frontiers in Environmental Science: Freshwater Science*. https://doi.org/10.3389/fenvs.2019.00037

**Appendix 1.** Qualitative analysis description

Sustainability science provides the overarching research design for the LIVES project produced by these initial sessions and the project was implemented with the following characteristics (as per Filho et al. 2016, Clark et al. 2016):

- Exploratory, action research approach with the goal of generating new fundamental science for understanding the governance of interlinked water, energy and food resources.
- Multi-, inter- and trans-disciplinary approaches used at different phases of the project cycle with a focus on knowledge co-production techniques.
- Positivist context framing, normative inputs in research design.
- Integration of multiple knowledge sources and viewpoints in a systems perspective
- Recognition of system interactions, dynamics, transitions and uncertainty.
- Recognition and testing (where possible) of assumptions underpinning research design.
- Production of credible, legitimate and salient knowledge in a decision context.
- Learning oriented approach.

A reflexive approach led us to collect and store the following data throughout the project:

- Context analysis interviews commissioned at the Royal University of Agriculture at the beginning of the project in 2015.
- Stakeholder evaluation reports, meeting summaries and other documents from 5 stakeholder workshops held in the landscape between January 2015 and July 2016, and 5 workshops held between February and December 2017, including the final project workshop in Phnom Penh.
- 15 interviews with close project collaborators, following the Most Significant Change method to elicit observations about changes generated by the project (including stakeholder attitudes, interactions and risk perceptions), mindful of the social, political and historical context for the case study. The project collaborators included representatives from Luc Hoffmann Institute, the General Secretariat to the National Council WWF Cambodia, the Royal University of Phnom Penh (in Cambodia), the Royal University of Agriculture (in Cambodia).

## Table A1.1 Stakeholder feedback and workshop meeting reports (Sources of 'SF' documents listed above in Table A2.1)

| Document code: | SF1-provincial day | SF1-farmers' day | SF2-Phase 1 Final WS | SF4-Kratie | SF4-Stung Treng | SF5-Kratie | SF5-Stung Treng | SF6 | MSC |
|---|---|---|---|---|---|---|---|---|---|
| **Relevant dates:** | 17.03.16 | 18.03.16 | 19-21.07.16 | 20-21 02.17 | 23-24 02.17 | 13-14 03.17 | 16-17. 03.17 | 08.12. 17 | 11.17-01.18 |
| **Project partners and participants** | | | | | | | | | |
| Cambodia-based LIVES project academic colleagues* | 1 | 1 | 2 | 1 | 1 | 1 | 1 | | 3 |
| Cambodia-based LIVES project WWF colleagues* | 5 | 5 | 9 | 4 | 7 | 4 | 4 | 6 | 7 |
| International WWF colleagues* | 1 | 1 | 2 | | | | | | |
| International LIVES academic colleagues * | 3 | 3 | 2 | | | | | 1 | |
| General Secretariat to the National Council on Sustainable Development Staff * | 7 | 7 | 5 | 9 | 9 | 6 | 7 | 5 | 3 |
| Ministry of Interior/ General Secretariat to the National Council on Subnational Democratic Development staff [national & provincial based] | | | | 2 | 2 | 2 | | 2 | |
| Ministry of Environment reps | | | 5 | 1 | 1 | 1 | 1 | 1 | |
| Ministry of Planning reps | | | | | | | | 4 | |
| Provincial government departmental officials, Kratie | 15 | | 12 | 9 | 16 | 5 | | 7 | |
| Provincial government departmental officials, Stung Treng | 14 | | 7 | | | | 4 | 7 | |
| Other Cambodian provincial officials | | | 2 | | 2 | | | | |
| District representatives, Kratie | 3 | 1 | 4 | 4 | | | | | |
| District representatives, Stung Treng | 3 | | 3 | | 3 | | | | |
| Other NGO staff members, Kratie & Stung Treng | 8 | | 12 | 3 | 1 | 1 | | | |
| Commune representatives, Village/community representatives/Local economic sectors (tourism, fishing, farming), Kratie | 1 | 4 | 4 | 1 | | 3 | | | |
| Commune representatives, Village/community representatives/Local economic sectors (tourism, fishing, farming), Stung Treng | 1 | 5 | 5 | | | | 5 | | |
| International and intergovernmental organisations staff based primarily in Phnom Penh | | | 2 | 3 | | | | 2 | |
| LIVES project management team | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 2 |
| **Male/Female** | **45/18** | **10/18** | **56/13** | **32/6** | **34/8** | **18/6** | **13/10** | **27/10** | **11/4** |
| **Total number of people** | **63** | **28** | **78** | **38** | **43** | **24** | **23** | **37** | **15** |
| **Total number of documents** | **2** | | **3** | **1** | | **2** | | **2** | **15** |

## MOST SIGNIFICANT CHANGE INTERVIEW PROTOCOL

The most significant change technique is a form of participatory monitoring and evaluation. It is participatory because many project stakeholders are involved both in deciding the sorts of change to be recorded and in analyzing the data. The process typically involves three major steps: 1) the collection and verification of stories from the field level for a particular time period, and 2) the systematic selection of the most important of these by panels of designated stakeholders or staff, 3) once changes have been captured share stories and have regular and often in-depth discussions about the value of the reported changes (Dart and Davies 2003, Willets and Crawford 2007). Users of this method must choose to pre-define specific domains of change they are expecting to observe or let these domains of change emerge from the field-level stories. When the technique is implemented in programmed design and delivery over the long term, this approach complements other forms of monitoring and evaluation while enabling teams to share and focus on particular forms of impact that are sometimes difficult to capture or measure in complex or long term social change processes.

In our research context, we adjusted these steps to:

- Collecting stories from individual team members and asking for means of verification during interview (November 2017– January 2018).
- Letting domains of change emerge through preliminary analysis (5-6 December 2017)
- Feeding back the results (8 December 2017) to a group representing the majority of interviewees to discuss most significant changes and verify preliminary findings.
- Secondary analysis of stakeholder feedback contained in evaluations and meeting documents (March – June 2018).

We performed one round of interviews in December 2017 asking interviewees to reflect on whole Cambodia pilot implementation from the beginning of their involvement to the end of Phase II in December 2017. Our most significant change interview questions and protocol are as follows:

Suggested script 1: about the MSC method

> Good morning (afternoon). Thank you for agreeing to do this interview. We are interested in speaking with you as a contributing member of the LIVES project team here in Cambodia. Today

Suggested script 2: explaining the interview format and how responses are recorded

> There are no right or wrong or desirable or undesirable answers or stories. Questions asked in informal interview style to enable us to dialogue. [NOTE: We do not force or lead interviewees to talk about specific domains - these should emerge from the interviewees themselves.]. If it is okay with you, I [project team member 1] will be recording your responses for content and substance, while [project team member 2] will record verbatim notes. We will also be recording the interview. The data will be used to as part of the LIVES research activities to help us evaluate the participatory system dynamics method. When we do the analysis, we will give this document a code number and we will not use your name.

Script 3: MSC questions

- Tell me how you first became involved with the LIVES project in Cambodia and what your involvement was?
- From your point of view, tell me a story that best describes the most significant change that has resulted from the LIVES project.

  Script 3.1: This can be negative or positive changes. Examples could be changes you have seen in others, a change in the way you think, a change in the way of working etc. You're welcome to add personal / professional changes.

- Why are this change/these changes significant for you?
  Instruction: If the list of changes have been long, recap for the interviewee before posing this question.

- What were the factors that helped bring about this change/these changes?
  Script 3.2: this can be internal factors e.g. to do with how the project was designed/implemented/ managed or it can be external factors e.g. the political context / structures of government /willingness of government officials

- Were there any barriers?
  Script 3.3: were there any barriers to bringing about the most significant change (s)? These can be internal or external barriers.

- Can you give us one example of a concrete change you made in your own professional working life as a result of the LIVES project?
- Is there a change you would like to make but have not been able to make as yet? For what reason?
- Is there anything else you'd like to add?

Two interviewers took separate sets of notes that were later merged into one narrative text, with support from audio recordings. Interviews were conducted in English, which is not the native language for the majority of project partners. For some interviews, we had translation assistance from other project team members. The priority in preparing the final narrative and reporting quotes was keeping the voice of the project partners.

Our preferred means of verification is triangulation where find at least two other concrete examples of evidence that supports the story. Example: if there is a claim that new capacity has been created in the person, can we find an example where they have clearly demonstrated this new capacity and can we get feedback from their peers or manager that they have observed this new capacity.

## QUALITATIVE ANALYSIS SOFTWARE AND DATA CODING

We used computer-assisted qualitative analysis [ATLAS.ti software package] (Freise 2014, 2016). For this particular analysis, an in vivo coding approach was used to the first reading of our data (King 2008, Saldaña 2016) to bring our project partner and participant viewpoints into the discussion of the modeling results discussion with statements that illustrated:

1. Prioritization of risks, and changing risk perceptions attributed to the processes
2. Reference to subnational development planning procedures, this being the ongoing decision making process where government choices are made on policy implementation and resource allocations relevant to water, energy, food and livelihood security.
3. Understanding of ownership, suggested actions for proceeding with using the new knowledge produced in the scenario and dynamic modelling.

The lead researcher recorded ideas and thoughts throughout the analysis process that were then synthesized to contribute to the initial understanding of nexus risk prioritizations by Mekong Flooded Forest stakeholders and the discussion of the modelling results in the main paper. This method is a form of grounded theory method, whereby codes and concepts emerge from the data (Saldaña 2013). While the final quotes selected reflect a certain view, they are always confirmed by other sources, i.e. other stakeholder opinions, national policy documents.

## LIMITATIONS

Knowledge integration and co-production happens in power dynamics arising from visible and invisible social, political and cultural structures (Giddens 1984, Lukes 2004). We know group processes affect how participants externalize their risk perceptions (Rouwette 2017). Also, that research teams are rarely neutral agents in transdisciplinary research (Pohl et al. 2010, Wesselink et al., 2013). We are fully aware that if you work within the social and political context, as we were, no activity is a neutral player (Wesselink et al. 2013) and inevitably some biases were likely to have been introduced through the relationships developed between project team members who were interviewing and those being interviewed.

Moreover, participatory monitoring methods are normally repeated and field experiences suggest that understanding of the approach and quality of story recounting and gathering improves over time whereas we used it just once (Willets and Crawford 2007). Secondly, the MSC method was not applied extensively. For example, we focused on collecting stories of change from close project partners and not our participants given time and other resource constraints. We assumed our interviewees' observations about changes for provincial and community participants would be an adequate proxy for these 'voices', as long as we supplemented them with a secondary analysis of the stakeholder evaluations and other feedback recorded in our workshop meeting reports. Moreover, we assume that our diverse project partner group lends the MSC data some robustness.

## LITERATURE CITED IN APPENDIX 1

Clark, W.C., L. van Kerkhoff, L. Lebel, and G. C. Gallopin. 2016. Crafting Usable Knowledge for Sustainable Development. *Proceedings of the National Academy of Sciences* 113(17):4570–4578. https://doi.org/10.1073/pnas.1601266113.

Friese, S. 2014. *Qualitative Data Analysis with ATLAS.ti.* 2nd edition. Sage, London.

Friese, S. 2016. CAQDAS and Grounded Theory Analysis. *MMG Working Paper* 16-07. ISSN 2192-2357 [online] URL: www.mmg.mpg.de/workingpapers.

Giddens, A. 1984. *The Constitution of Society: Outline of the Theory of Structuration*. University of California Press, Berkeley.

Glaser B. G. and A. L. Strauss. 1973. *The Discovery of Grounded Theory : Strategies for Qualitative Research.* Eldin, Chicago.

Hsieh, H.-F. and S.E. Shannon. 2005. Three approaches to qualitative content analysis. *Qualitative. Health Research.* 15, 1277–1288.

King, A. 2008. InVivo Coding. In Given, L.M., editor. *The SAGE Encyclopedia of Qualitative Research Methods* SAGE Publications, Thousand Oaks doi: 10.4135/9781412963909.n240.

Leal Filho, W., R. W. Marans, and J. Callewaert. 2017. *Handbook of Sustainability and Social Science Research*. World Sustainability Series. Springer International Publishing. [online] URL: http://www.springer.com/series/13384.

Lukes, S. 2005. *Power: A Radical View, 2ed.* Palgrave Macmillan Ltd., Basingstoke, Hampshire. [online] URL: http://voidnetwork.gr/wp-content/uploads/2016/09/Power-A-Radical-View-Steven-Lukes.pdf

Rouwette, E. A. J. A. 2017. The impact of group model building on behavior. In M. Kunc, J. Malpass and L. White, editors. *Behavioral Operational Research: Theory, Methodology and Practice* Palgrave Macmillan UK, London: 213-241.

Saldaña, J.2013. *The coding manual for qualitative researchers.* Second edition. SAGE Publications, London.

Wesselink, A., K. S. Buchanan, Y.Georgiadou and E.Turnhout 2013. Technical Knowledge, Discursive Spaces and Politics at the Science–Policy Interface. *Environmental Science & Policy* 30: 1–9.

Willetts, J., and P. Crawford. 2007. The Most Significant Lessons about the Most Significant Change Technique. *Development in Practice* 17(3):367–79. https://doi.org/10.1080/09614520701336907.

## **Appendix 2.** Further information on model group building process, model structure and data

We intend to publish the model in a separate research article, however we share some of the details of how the model was built and tested with stakeholders for the interested reader here in two parts:

- Description of the participatory model development process.
- Simulation model description.

### PARTICIPATORY MODEL DEVELOPMENT PROCESS

The MFF Causal Loop Diagram (CLD) co-creation process aimed to explore the systemic nature of the MFF landscape and identify points for policies and investment interventions with those actors who are directly engaging with nexus risk governance in our case study location. The intention was to create a shared understanding among national and provincial stakeholders of the main drivers of change in the MFF landscape, while also integrating dispersed data, knowledge about the landscape and different perspectives on risks and feasible responses. Background work on the aggregated CLD and simulation model continued in parallel from the beginning and helped shape the stakeholder sessions so this process should be thought of as an iterative one whereby model development and stakeholder learning influence each other.

Multiple CLDs were created through sessions that were facilitated both in English and Khmer. A CLD is normally created with 10-30 people in two to three hours. Ideally, all relevant stakeholders would participate in a single group model building session. However, finding suitable venues, dates and times is a challenge, especially with the numbers of stakeholders in the MFF manifestation of the Mekong nexus and when the presence of multiple line ministry staff, provincial departments, and district and communes representatives are required. Moreover, we anticipated that cultural hierarchy and other power dynamics could potentially impact how people shared their information and views and preferred to hold separate sessions at times. As a result, several group model building sessions were organized with various mixes of stakeholder groups from October 2014 – April 2016 and a final review workshop was held in July 2016.

Table A2.1. sets out the various meetings and how stakeholders engaged with the model development process.

## Table A2.1 Stakeholder and model development interactions

| Meeting date and location | Meeting Description | Stakeholder - model development interactions |
|---|---|---|
| 28-29 January, Phnom Penh and Kratie | Introduction session mixing National Council for Sustainable Development and Ministry of Environment staff, WWF staff and Royal University of Agriculture and Royal University of Phnom Penh researchers. Introduction session mixing provincial departments from both Kratie and Stung Treng with trial CLD building procedure. Stakeholder identification process launched. | Basic CLD constructed, initial identification of stakeholder priorities, risk perceptions and concerns. Stakeholders identified for the later sessions. |
| 30 March - 3 April 2015, Phnom Penh and | Train the Trainers pre-workshop event<br>Values and Threats exercises to identify key variables (indicators), training on green economy and ecosystem services concepts (requested by Provincial Administrations in January 2015), followed by CLD development session with mixed provincial departments from both Kratie and Stung Treng province administrations, policy intervention discussion and data needs analysis. | Inputs to aggregated CLD preparation. Key nexus interactions and scenarios of interest to stakeholders identified. |
| 28-29 May 2015, Phnom Penh, Cambodia | Review meeting with regional and national experts sharing some early ground work, refining larger project research objectives and approach and continuing the process of compiling data and identifying stakeholders for later outreach and engagement at regional and national levels. | Aggregated CLD review and national-level data collection. Feedback on proposed scenarios. |
| 28 September – 10 October 2015, Stung Treng Provincial Hall, Stung Treng Town. | Train the Trainers pre-workshop 2-day event, followed by a 2-day CLD development session with mixed provincial departments from both Kratie and Stung Treng province administrations. | Aggregated CLD review and refinement, and extension with policy and other response intervention points. Key nexus interactions and scenarios of interest to stakeholders identified. Provincial data collection objectives set and national Ministry of Environment colleague allocated task. |
| 25-28 April 2016, Phnom Penh | A series of meetings discussed project progress, outputs and future financing, while meeting stakeholders in the capital working on national policy activities. | Model development progress check. Review of policy interventions and upcoming opportunities at national level. Refinement of policy and other responses in aggregated CLD. Environmental flows scenario identified as important to civil society groups. |
| 14-18 March 2016, Kratie Town | Values and Threats exercises to identify key variables (indicators), followed by CLD development session with district, commune and civil society stakeholders. | Inputs to aggregated CLD preparation. Review and finalisation of key variables and responses. Alternative crops scenario identified as relevant and important. |
| 19-21 July 2016, Sihanoukville | Final workshop reviewing and refining aggregated CLD, preliminary scenario analyses, data with both Kratie and Stung Treng provincial stakeholders, staff from Ministry of Environment and secretariat to the National Council for Decentralisation and Deconcentration, International and local civil society groups. | Review of nexus interaction-related indicators for the MFF and preliminary scenario analysis results for the Scenario 1- Baseline (without dam) and Scenario 2 - Baseline with Stung Treng Dam. Feedback on data quality and directions for future analysis priorities. |

## MFF MODEL DESCRIPTION

The multiple stakeholder CLDs were analyzed to elicit (i) stakeholder assumptions, perceptions about critical variables for the MFF nexus and their interactions; (ii) priority concerns held by stakeholders; and (iii) possible intervention points which were then aggregated (Luna-Reyes et al. 2006) and used to inform the computational model-building. Practically, the creation of the mathematical model serves also to validate the correctness and quality of the CLD because data and equations confirm or invalidate the linkages (and/or their polarity) included in the CLD.

### Model stocks and flows

The first step in the creation of the mathematical model was to identify stocks and flows from an aggregated CLD. The main stocks and flows included in the model are:

- *Human population*, influenced by birth, death and net migration (affected by the availability of settlement land and by the construction and operation of the hydropower dam which generates employment opportunities and facilitates inward migration of construction workers);
- *Fish population*, influenced by breeding, mortality, net migration (affected by dam capacity) and catch (affected by fish demand);
- *Dolphin population*, influenced by breeding and mortality (affected by dam capacity);
- *Land* (settlement, agriculture, grazing and fallow/forest land), influenced by population and food demand (i.e. demand for land-based food production like crops and meat drives allocation of land to cultivation). Food demand and supply are disaggregated into crops, meat and fish. Agricultural households in this region typically produce for both subsistence and for local and regional markets.
- *Sediments*, influenced by water diversions (affected by population, precipitation and hydropower investments), land clearing (affected by population and yield) and the extraction of construction materials (e.g. sand and gravel);
- *Flow regime,* represented by water diversions (affected by population, precipitation and hydropower investments), land clearing of forest land (affected by population and yield).
- *Water* is represented by diversion, for its use in agriculture production as its function in supporting the fish and human population (e.g. through water quality).
- *Hydropower dam capacity*, influenced by the assumed investment in capacity expansion (the decommissioning/discard of capacity is not assumed to take place due to the long life time of capital and the simulation time reaching only 2040).
- *Energy* is represented by the construction of a hydropower dam (and its power output), which in turn affects food demand (especially if electricity is provided to the local population) and supply (e.g. fish and agriculture).
- *Road network length*, influenced by the assumed investment in capacity expansion and decommissioning/discard.
- *Hydropower economic indicators,* influenced by the capacity of the hydropower dam, tracking its financial value and the cash flow resulting from operations. This includes revenues (affected by production and the price of electricity) and costs (affected by planned operation and management activities as well as sedimentation).

Mathematically, the basic structure consists of a system of coupled, nonlinear, first-order differential equations to describe the rate of change of stock variables (Richardson 1991). The Green Economy Model (Bassi 2015) was drawn on for its explicit representation of stocks of built, human, social and natural capital. The UN Population Division model for World Population Prospects using birth, death and migration was applied to human, fish and dolphin populations. Electricity generation capacity was included using the International Energy Agency's MARKAL model (MARKet and ALlocation: a technology explicit, dynamic partial equilibrium model of energy markets). MARKAL was selected over its IEA-provided alternative, TIMES, because the economic sub-model of TIMES is not customizable to the sub-national scale at which our study is focused. MARKAL is available at: https://iea-etsap.org/index.php/etsap-tools/model-generators/markal.

Most factors are already represented in the CLD but additional work was required to operationalize the mathematical model. In other words, the mathematical model needs to include equations that represent local dynamics in a coherent manner, based on existing data, peer-reviewed papers, report and local knowledge. As a result, the mathematical model is built off a considerably higher number of variables compared to the CLD.

### Model data sources

An NCSD secretariat colleague met with sectoral provincial departments in Kratie and Stung Treng to collect provincial data containing 50 time-series variables (of varying quality) including: economic activities and related energy consumption; dolphin populations; local market prices for crops, meat and fish; and tourism arrivals with average expenditure per tourist visit. National statistics and policies provided land cover, population and other socio-economic data, climate data and scenarios. IEA data was used to estimate construction, operation and maintenance cost of hydropower dams, in conjunction with plant specific data for Kratie and Stung Treng developments (Wu et al. 2010). Peer-reviewed literature from the Mekong region supported assumptions made on electricity supply influence on income (Khandker et al. 2013) and climate change impacts on agriculture productivity (e.g. Dang et al. 2016, Thilakarathne and Sridhar 2017). Remaining data gaps were filled through consultations with national researchers, government officials, civil society staff and local communities. In cases where the local partners felt national data did not represent the provinces, adjustments were made to favor the perspectives of Stung Treng and Kratie stakeholders. The following sources support model assumptions and quantification:

Bassi, A., E. Bečić and Lombardi 2014. An introduction to the assessment of sustainable paths, models and metrics. *Asian Social Science* 10(11):17-27.

Bezuijen, M.R., R.J. Timmins and T. Seng. 2007. Biological surveys of the Mekong River between Kratie and Stung Treng towns, northeast Cambodia 2006-2007, WWF-Greater Mekong. Cambodia Country Programme.

Buckley, B. M., K. J. Anchukaitis, D. Penny, R. Fletcher, E. R. Cook, M. Sano, L. C. Nam, A. Wichienkeeo, T. T. Minh, and T. M. Hong. Climate as a Contributing Factor in the Demise of Angkor, Cambodia. *Proceedings of the National Academy of Sciences* 107(15): 6748–52.

Cook, B.I., and B.M. Buckley. 2009. Objective Determination of Monsoon Season Onset, Withdrawal, and Length. *Journal of Geophysical Research* 114(D23).

Costanza, R., H. Daly, C. Folke and K. Maler. 1993. Modeling complex ecological economic systems: towards an evolutionary dynamic understanding of people and nature. . *BioScience* 43: 545-555.

de Groot, R., R. Alkemade, L. Braat, L. Hein and L. Willemen. 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity* 7(3): 260-272.

Goodenough, R., and S. Page. 1994. Evaluating the environmental impact of a major transport infrastructure project: the Channel Tunnel high-speed rail link. *Applied Geography*: 26-50.

Halls, A.S., and M. Kshatriya. 2009. *Modelling the Cumulative Barrier and Passage Effects of Mainstream Hydropower Dams on Migratory Fish Populations in the Lower Mekong Basin.* Mekong River Commission, Vientiane.

Hoang, L.P., H. Lauri, M. Kummu, J. Koponen, M.T.H. van Vliet, I. Supit, R. Leemans, P. Kabat, and F. Ludwig. 2016. Mekong River flow and hydrological extremes under climate change. *Hydrology and Earth System Sciences* 20: 3027–3041.

ICEM 2010. MRC *Strategic Environmental Assessment (SEA) of hydropower on the Mekong mainstream: summary of the final report*, International Centre for Environmental Management, Viet Nam. [online] URL: http://www.mrcmekong.org/assets/Publications/Consultations/SEA-Hydropower/SEA-FR-summary-13oct.pdf

Mekong River Commission (MRC), Cambodia National Mekong Committee (CNMC), and International Centre for Environmental Management (ICEM). 2015. Cambodia Climate Change Toolbox. Generated under the Cambodia: mainstreaming climate resilience into development planning. Sovereign (Public) Project 45283-001. Asian Development Bank, Manila, Philippines. [online] URL: https://dss.icem.com.au/CambodiaDSS/

IRENA 2018. *Renewable Energy Market Analysis: Southeast Asia*, International Renewable Energy Agency, Abu Dhabi. Downloaded June 2018. [online] URL: https://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_Market_Southeast_Asia_2018.pdf

Isely, E., P. Isely, S. Seedang, K. Mulder, K. Thompson, and A. Steinman. 2010. Addressing the information gaps associated with valuing green infrastructure in west Michigan: INtegrated Valuation of Ecosystem Services Tool (INVEST). *Journal of Great Lakes Research* 36(3): 448-457.

Jones, H., F. Moura and T. Domingos. 2014. Transport infrastructure project evaluation using cost-benefit analysis. *Procedia - Social and Behavioral Sciences* 111: 400-409.

Khandker, R.S., D.F. Barnes, and H.A. Samad. 2013. Welfare impacts of rural electrification: a panel data analysis from Vietnam. *Economic Development and Cultural Change* 61(3):659-692.

Korytárová, J. and V. Hromádka. 2014. The economic evaluation of megaprojects – social and economic impacts. *Procedia - Social and Behavioral Sciences* 119:495-502.

Makki, T., S., Fakheran, H. Moradi, M. Iravani and J. Senn. 2013. Landscape-scale impacts of transportation infrastructure on spatial dynamics of two vulnerable ungulate species in Ghamishloo Wildlife Refuge, Iran. *Ecological Indicators* 31:6-14.

MEA. 2005. *Ecosystems and Human Well-being: General Synthesis.* Island Press & World Resources Institute, Washington D.C.

Misra, V. and S. DiNapoli. 2014.The variability of the southeast Asian summer monsoon *International Journal of Climatology* 34, no. 3 (March 15, 2014): 893–901.

MRC. 2017. The study on sustainable development and management of the Mekong river, including the impacts of mainstream hydropower projects. Mekong River Commission, Vientiane. [online] URL: http://www.mrcmekong.org/news-and-events/events/the-regional-stakeholder-forum-on-the-council-study-updated-pdg-and-sustainable-hydropower-development-strategy/

Noldan, B., S. Janoušková, and T. Hák. 2012. How to understand and measure environmental sustainability: Indicators and targets. *Ecological Indicators* 17:4-13.

Opperman, J., J. Hartmann, J. Raepple, H. Angarita, P. Beames. E. Chapin, R. Geressu, G. Grill, J. Harou, A. Hurford, D. Kammen, R. Kelman, E. Martin, T. Martins, R. Peters, C. Rogéliz, and R. Shirley. 2017. *The power of rivers: A business case*. The Nature Conservancy, Washington, D.C.

Pearse-Smith, S. 2012. The impact of continued Mekong basin hydropower development on local livelihoods. *The Journal of Sustainable Development* 7(1):73-86.

Poff, N. L and J. H. Matthews. 2013. Environmental flows in the Anthropocene: past progress and future prospects. *Current Opinion in Environmental Sustainability* 5(6):667–75.

RGC. 2001. *Vulnerability and Adaptation Assessment to Climate Change in Cambodia.* Ministry of Environment, Royal Government of Cambodia, Phnom Penh.

RGC. 2003. *National Population Policy 2016-2030*. Ministry of Planning. Royal Government of Cambodia, Phnom Penh.

RGC. 2008. *The Rectangular Strategy for Growth, Employment, Equity, and Efficiency in Cambodia.* Ministry of Planning. Royal Government of Cambodia, Phnom Penh.

RGC. 2010. *Fisheries Strategic Planning Framework 2010-2019.* Ministry of Agriculture, Forestry and Fisheries. Royal Government of Cambodia, Phnom Penh.

RGC. 2011a. *Kratie provincial development planning 2011-2015*, Kratie provincial administration unit, Royal Government of Cambodia, Kratie.

RGC. 2011b. *Stung Treng provincial development planning 2011-2015*, Stung Treng provincial administration unit, Royal Government of Cambodia, Stung Treng.

RGC. 2012. *Cambodia Socio-Economic Survey.* National Institute for Statistics. Royal Government of Cambodia. online] URL: https://www.nis.gov.kh/index.php/en/about/general-information/14-cses/12-cambodia-socio-economic-survey-reports

RGC. 2012. *The Cambodian Government's Achievements and Future Direction in Sustainable Development: National Report for Rio+20, United Nations Conference on Sustainable Development*. Ministry of Environment. Royal Government of Cambodia, Phnom Penh. [online] URL: https://sustainabledevelopment.un.org/content/documents/1022cambodia.pdf

RGC. 2013. *Statistical Yearbook*, National Institute for Statistics, Royal Government of Cambodia, Phnom Penh. online] URL: https://www.nis.gov.kh/index.php/en/

RGC. 2014. *Cambodia Socio-Economic Survey.* National Institute for Statistics. Royal Government of Cambodia, Phnom Penh. [online] URL: https://www.nis.gov.kh/index.php/en/about/general-information/14-cses/12-cambodia-socio-economic-survey-reports.

RGC. 2015. *Agricultural Sector Strategic Development Plan 2014-2015*. Ministry of Agriculture, Forestry and Fisheries, Royal Government of Cambodia, Phnom Penh.

RGC. 2016. *National Climate Change Action Plan*. Ministry of Environment, Royal Government of Cambodia, Phnom Penh.

RGC. 2016a. *DRAFT Cambodia Energy Sector Strategy*. Ministry of Industry, Mines and Energy. Royal Government of Cambodia, Phnom Penh.

RGC. 2016b. *Cambodia National Energy Statistics*. Ministry of Industry, Mines and Energy. Royal Government of Cambodia, Phnom Penh.

RGC. 2016c. *National Climate Change Action Plan. Ministry of Environment*. Royal Government of Cambodia, Phnom Penh.

Richter, B. D. and G. A. Thomas. 2007. Restoring environmental flows by modifying dam operations. *Ecology and Society* 12(1): 12.

Singh, S., R. Boonratana, M. Bezuijen and A. Phonvisay. 2006. *Trade in Natural Resources in Stung Treng Province, Cambodia: An assessment of the wildlife trade.* TRAFFIC. MWBP. Vientiane, Lao PDR. Available from: www.mekongwetlands.org https://portals.iucn.org/library/sites/library/files/documents/Traf-098.pdf

Sivhuoch, O., and C. Sreang. 2015. *Analysis of Cambodia's Preparedness for the Implementation of Sustainable Development Goals: Challenges, Opportunities and Financing* Commissioned by the Cooperation Committee for Cambodia September, 2015. Partnerships for Sustainable Development in Cambodia. [online] URL: http://ticambodia.org/library/wp-content/files_mf/1448900988AnalyseSDGsforCambodiaFinal.pdf.

Sotharith, C. 2014. Cambodia country report. In Zen, F. and M. Regan (eds.) 2014. *Financing ASEAN Connectivity*, ERIA Research Project Report No.15, Economic Research Institute for ASEAN and East Asia, Jakarta: 63-102.

Thoeun, H. C. 2015. Observed and projected changes in temperature and rainfall in Cambodia. *Weather and Climate Extremes* 7: 61–71.

Thomas, T.S., T. Ponlok, R. Bansok, T. De Lopez, C. Chiang, N. Phirun and C. Chhun. 2013. *Cambodian agriculture and adaptation to climate change impacts.* IFPRI Discussion Paper 01285. Washington DC, USA. [online] URL: https://reliefweb.int/sites/reliefweb.int/files/resources/Cambodian%20agriculture%20adaptation%20to%20climate%20change%20impact.pdf

Thompson, J.R. C.L.R. Laizé, A.J. Green, M.C. Acreman and D.G. Kingston. 2014. Climate change uncertainty in environmental flows for the Mekong River. *Hydrological Sciences Journal* 59:3-4: 935-954. https://doi.org/10.1080/02626667.2013.842074

Ulgiati, S., A. Zucaro and P. Franzese. 2011. Shared wealth or nobody's land? The worth of natural capital and ecosystem services. *Ecological Economics 70*(4): 778-787.

UN FAOSTAT 2018. Food and Agriculture Organisation of United Nations (FAO), Rome, Italy. [online] URL: http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor (last accessed 21.06.18).

UN Population Division 2017. *World population prospects.* Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. [online] URL: https://esa.un.org/unpd/wpp/.

Urban, F., G. Siciliano, K. Sour, P. D. Lonn, M. Tan-Mullins and G. Mang. 2015. South-south technology transfer of low-carbon innovation: Large Chinese hydropower dams in Cambodia *Sustainable Development* 23(4): 232–44.

Van Paddenburg, A., A. Bassi, E. Buter, C. Cosslett and A. Dean. 2012. *Heart of Borneo. Investing in Nature for a Green Economy.* WWF, Switzerland.

Vandermeulen, V., A. Verspecht, B. Vermeire, G. Van Huylenbroeck and X. Gellynck. 2011. The use of economic valuation to create public support for green infrastructure investments in urban areas. *Landscape and Urban Planning* 103(2): 198-206.
Wallhagen, M. and M. Glaumann. 2011. Design consequences of differences in building assessment tools: a case study. *Building Research & Information* 39(1): 16-33.
Hoekstra, A. Y., and M. M. Mekonnen. 2012. The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America* PNAS 109(9): 3232-3237.
UN FAOSTAT. 2018. Food and Agriculture Organisation of United Nations (FAO), Rome, Italy. [online] URL: http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor (last accessed 21.06.18).

## Model calibration, validation and assessment of uncertainty and sensitivity

The calibration of the model was performed considering the fit with data of a variety of indicators, both in isolation (i.e. one variable at a time) and in a systemic way (i.e. ensuring that all variables simultaneously would match historical data and trends). The validation of the MFF model was performed using different methods: (i) formal structural and (ii) behavioral validation as well as (iii) stakeholder engagement in the review and analysis of simulation results. Examples of direct structure tests that were performed include structure confirmation tests (i.e. comparison of the equations utilized with literature); and parameter confirmation tests (i.e. comparison of the constant or initial factors utilized with national and provincial databases and published research). Additional tests conducted include direct extreme-conditions test. Behavior sensitivity tests and phase-relationship tests were also performed to ensure that the model would not lead to perpetual exponential growth or decay even under extreme parametrization. In other words, this test ensures that the feedback loops in the model are correctly calibrated and respond to (i.e. counterbalance) emerging changes in the system.

Assessing the sensitivity of System Dynamics models is challenging due to the presence of several feedback loops. As one example, the variable “agriculture land” alone is affected by 645 feedback loops in the MFF model, which would need to be assessed for 16 time steps per year over 40 years of the simulation which is not recommended (Saleh et al. 2005). When assessing the simulation results however, it is possible to easily identify dominant feedback loops and how they change due to the implementation of an external action and how this propagates through the model. In other words, while agriculture land is affected by 645 feedback loops, only two or three of them really drive behavior in that variable. Figure A1.2 shows a simplified representation of the MFF model. The dominant feedback loops suggested by the dynamic simulation to be driving the development trajectory in the landscape is the interplay between **availability of natural capital** (e.g. fish stock, forest land, agriculture land) that has enabled a stable level of productivity and supported growth in natural resource-based economic activities and **Physical infrastructure investments** like hydropower dams and supporting roads.

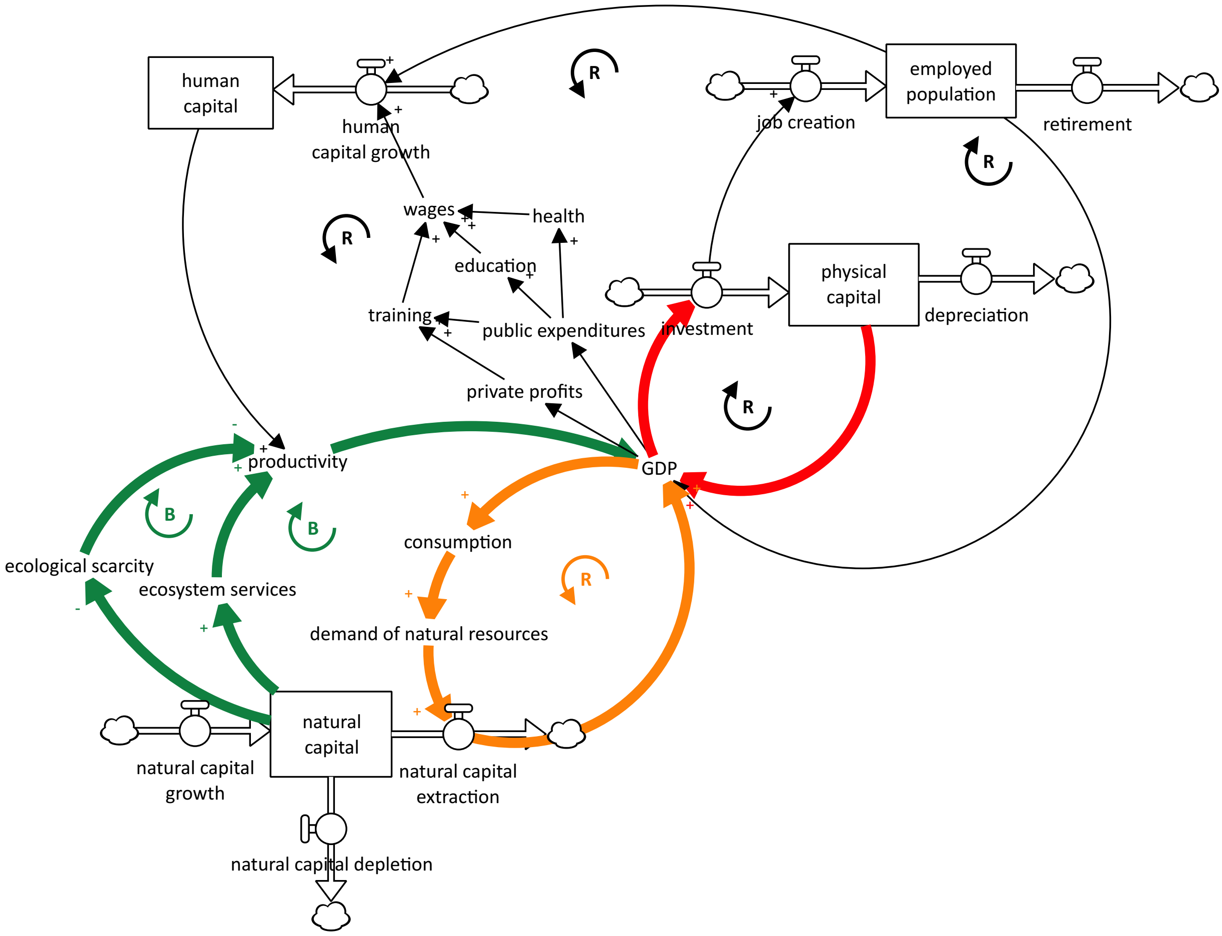


**Fig. A2.2:** Simplified representation of the key capital stocks and feedback loops dominating the simulated MFF system co-produced with stakeholders †
†Key stock variables are indicated by boxes. Feedback loops are noted by reinforcing (R) and balancing (B) behavior induced.

## ADDITIONAL LITERATURE CITED IN APPENDIX 2

Bassi, A. M. 2015. Moving towards integrated policy formulation and evaluation: The Green Economy Model (GEM). *Environmental and Climate Technologies* 16(1):5-18.

Khandker, R. S., D. F. Barnes, and H. A. Samad. 2013. Welfare impacts of rural electrification: A panel data analysis from Vietnam. *Economic Development and Cultural Change* 61(3):659-692.

Luna-Reyes, L. F., I. J. Martinez-Moyano, T. A. Pardo, A. M. Cresswell, D. F. Andersen, and G. P. Richardson. 2006. Anatomy of a group model-building intervention: Building dynamic theory from case study research. *System Dynamics Review* 22(4):291–320

Richardson, G. P. 1991. System dynamics: Simulation for policy analysis from a feedback perspective. In Fishwick, P. A. and P. A. Luker, editors. 1991. *Qualitative Simulation Modeling and Analysis* Springer Verlag, New York:144-169.

Saleh M., P. Davidsen, K. Bayoumi (2005). A Comprehensive Eigenvalue Analysis of System Dynamics Models. Proceedings of the 23rd International System Dynamics Conference (ISDC), Boston, July 17-21, 2005.