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 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:

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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.

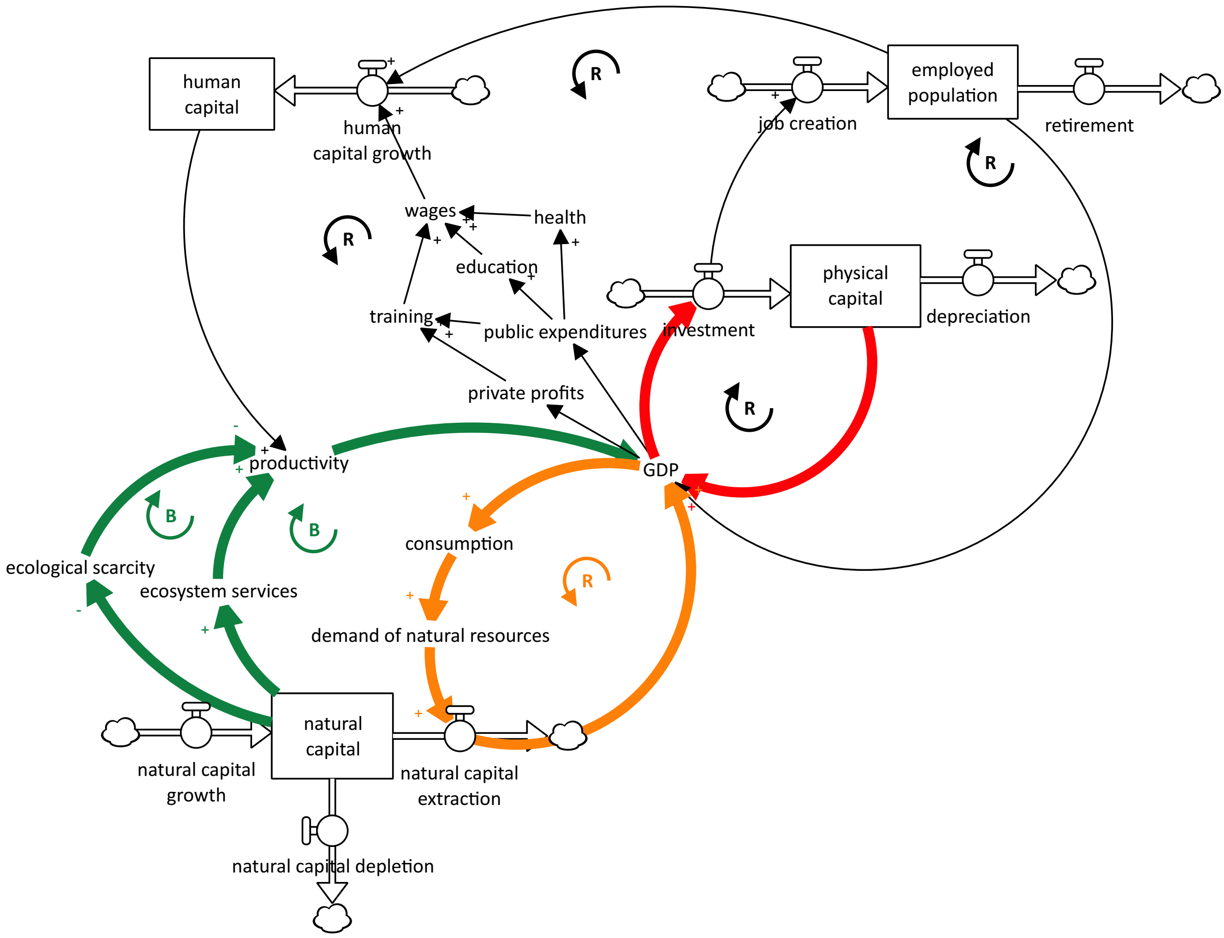

Fig. A2.2: Simplified representation of the key capital stocks and feedback loops dominating the simulated MFF system co-produced with stakeholders †
†Key stock variables are indicated by boxes. Feedback loops are noted by reinforcing (R) and balancing (B) behavior induced.

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