



# Applying Bayesian belief networks (BBNs) with stakeholders to explore and codesign options for water resource interventions

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## Abstract

Bayesian Belief networks (BBNs) are a useful tool to account for uncertainty and can be used to incorporate stakeholder understandings of how a system works. In this study, BBNs were applied to elicit and discuss local stakeholders' concerns in conflicts over water resource planning in two cases in southern Thailand. One concerned the construction of a dam proposed by a top-down project. The other concerned a bottom-up participatory process at the catchment scale to assess the need for water resources interventions and explore perceptions on alternative design options. In the top-down project, the responses of participants during the elaboration of the BBN showed that potentially affected stakeholders were particularly concerned about limited consultation and lack of shared benefits, which led them to oppose the dam project. In the bottom-up project, local stakeholders expected and agreed with the benefits of a dam, proposing to locate the dam upstream of community land. The BBN method did not facilitate dialogue in the top-down dam-building project because no alternative design options could be discussed and potentially affected stakeholders did not want to discuss compensation because of mistrust and differences in valuation of effects. In the bottom-up project, the BBN method did facilitate dialogue on alternative intervention options and their effects. The replicable BBN framework can support policy-makers to better understand water conflict situations in different stages of planning. Its application supports exploring a wider repertoire of options, enlarging the scope for more inclusive and sustainable solutions to water resource conflicts.

**Keywords** Bayesian belief network · Water resources planning · Stakeholder involvement · Conflicts · Policymakers

## Introduction

Water resources development may cause conflicts as stakeholders do not have compatible interests and may not easily reach consensus. To avoid the paralysis of the planning process, stakeholders' interests need to be carefully

considered. To find solutions, there is a need for stakeholders to find common ground in relation to problems and solutions in the early planning stages (Reed 2008). This way, alternatives can be proposed in a participatory process, empowering stakeholders who have different backgrounds, interests, knowledge, and perspectives to share ideas and negotiate better outcomes. Empowerment requires more attention to be paid to decision-making in the planning process (Julian et al. 1997). For example, to safeguard that proposed interventions support equity, sustainability and efficiency, relevant evaluation criteria should be included (Bromley et al. 2005). Outcomes for stakeholders further depend on how they are included in the decision-making process, e.g. whether they are only informed, or consulted and have had the chance to co-design interventions and make decisions (Singto et al. 2018).

Dams are often presented to stakeholders as interventions that will provide benefits (e.g. more irrigated farmland, more water storage capacity supporting irrigation

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and flooding mitigation, and more secure water supply for urbanization). Nevertheless negative environmental and societal impacts cannot be neglected, and are commonly described in Environmental Impact Assessment (EIA) reports. However, several studies find that stakeholders whose land is inundated by newly constructed reservoirs lose farm income due to poor livelihood assets after resettlement on new unproductive land (e.g. Bui et al. 2013; Devitt and Hitchcock 2010; Duarte-Abadía et al. 2015). Access to suitable agricultural land is crucial to set up a new livelihood after resettlement (Sayatham and Suhardiman 2015). Moreover, dams might negatively affect farm income because the social capital needed to adapt to the new situation is often lacking in resettlement contexts (Tilt and Gerkey 2016). These examples illustrate the concerns of affected stakeholders, which often leads to disagreement on positive and negative dam impacts. When concerns are adequately aired, solutions can be found. For example, Singer et al. (2014) mention that benefit sharing could be promoted, allowing project beneficiaries to reach out to affected stakeholder and mediate the negative impacts on their livelihoods.

In conflicts, affected stakeholders often claim that participatory tools are biased and limit their engagement in the dam planning process (Singto et al. 2018). Elicitation methods and discussions with affected people need to systematically improve to engage affected stakeholders (Van Asselt and Rijkens-Klomp 2002). To enable solutions in deadlock situations, policy-makers should hence carefully design more participatory processes. This premise underpins Participatory Integrated Assessment (PIA) which entails the systematic measurement of participatory processes for improving project planning (Ridder and Pahl-Wostl 2005). Modelling may be one method that can be deployed in a PIA to further engagement, manage conflicts and avoid negative impacts of proposed policies (e.g. Mahato and Ogunlana 2011), as ex-ante models can provide a safe environment for discussions about impact. Various models have been used with stakeholders to explore the likelihood of impacts and so support decision-making (Lynam et al. 2007). Bayesian Belief Networks (BBNs) are one such model that has been used in co-designing and planning of interventions (Bromley et al. 2005) but has so far rarely been applied in practice for dam planning. This paper poses the question: could Bayesian Belief Networks (BBNs) be a useful tool to facilitate participatory processes in conflict situations in dam planning projects?

BBNs are probabilistic models that represent a set of variables and their conditional dependencies. The relation between directly related variables is described in Conditional Probability Tables (CPTs). BBNs can combine socio-economic and environmental variables related to water into a framework and engage stakeholders in planning (Carmona et al. 2011).

Applying BBNs can enable estimation of possible future outcomes based on many variables, and information about the relations between variables (in the CPTs) can be updated (Castelletti and Soncini-Sessa 2007). BBNs can help estimate outcomes before alternatives are chosen and implemented (Levontin et al. 2011). Moreover, BBNs can manage qualitative data which other models cannot do. In addition, BBNs permit use of incomplete data variables in the network (Bouejla et al. 2014). Uncertainty of impacts from alternatives can be addressed in BBNs to support the choice of agreed solutions (Phan et al. 2016).

Bertone et al. (2016) used BBNs to deal with incomplete data and variables by involving experts and linking qualitative and quantitative data together in the participatory study of water quality risk assessment of reservoirs, investigating the sensitivity of effects related to alternative interventions options of interventions. Likewise, Carmona et al. (2013) used BBNs as a participatory modelling tool in water management allowing policy-makers to better understand local perspectives and be better able to consider the most acceptable options. BBN tools can make it easier to reconcile the various valuations and knowledge of participants in a more hypothetical way, which relieves some of the problems of dealing with sensitive issues.

The above experiences show significant potential for applying BBNs in the context of water resources planning, and in particular to deploy BBNs as a tool to engage stakeholders in decision making in conflict situations. However, so far, BBNs have been developed as case-specific tools without considering whether models can be designed so that they can be adapted to explore and co-design options for water resource interventions in multiple places. Therefore, this paper aims to a) develop a general BBN framework that can be used in a participatory planning process with stakeholders for planning water resource development projects; b) apply the framework to two distinct cases to test the adaptability of the general framework and document its adaptation process in participatory sessions with local stakeholders; and c) assess, based on stakeholder opinion and expert knowledge, the BBNs and their usefulness in the planning process.

## Bayesian belief networks for dam planning projects

BBNs are increasingly applied to support participatory decision making under uncertainty (Levontin et al. 2011), and are also becoming popular in water resources planning (Phan et al. 2016). BBNs can also be used for creating a framework to predict probability under uncertain situations (Roosbahani et al. 2018). One area of recent BBN application concerns decision-making, e.g. considering variables affecting stakeholder behaviour in an irrigation system (McKee 2015). BBNs are also applied to find agreeable solutions for water

conflicts among stakeholders; for example, by managing trade-offs between farming and environment to meet the EU Water Framework Directive targets in Spain (Zorrilla et al. 2010) and assessing the effects of a water pricing policy in northwest China (Mamitimin et al. 2015).

BBNs can be used when experts and stakeholders cooperate in developing graphical networks (Phan et al. 2016). Such networks can be used as a decision-support tool, facilitating intervention decisions based on enhanced understanding of the links between several variables (Hoshino et al. 2016). BBNs can also assess the impacts of proposed interventions as perceived by different stakeholders, which is particularly relevant in cases of conflicts over natural resources (Xue et al. 2017). In the case of uncertain or disputed impacts, tools need to be easily understood (and operated) by stakeholders, and allow them to include their knowledge and valuation in the assessment. This means that it is imperative to combine various sources of knowledge and not only allow numeric data (Phan et al. 2016). Stakeholder knowledge can, for example, inform the design of interventions for reducing uncertain expected negative impacts (Baillergeau and Duyvendak 2016).

BBNs are mostly developed using a software program to understand key issues affecting the performance of a system that may be represented by a mix of quantitative and qualitative variables (Lynam et al. 2007). A graphical network of variables relates causes and effects (parent and child variables) and highlights their relationships by arrows linking between them. BBNs accommodate the integration of variables with different scales (Ticehurst et al. 2007). In a BBN diagram, data for each variable is given in a CPT (Marcot et al. 2006). The relationships between variables defines the conditional probability in child variables (Levontin et al. 2011). When there is a lack of data, expert and stakeholder judgments can inform probability assessment for CPTs (Pollino et al. 2007). As such BBNs have the ability to integrate information from stakeholders as well as experts (Farmani et al. 2009; Keshtkar et al. 2013).

In developing BBNs with stakeholders, Bromley et al. (2005) used stakeholder consultation to construct preliminary networks incorporating stakeholder concerns through linking variables and determining states. These BBNs were then completed by collecting data for the CPTs. A CPT should have the fewest number of possible states to support ease of understanding (Cain 2001; Mamitimin et al. 2015), particularly when eliciting expert knowledge (Chen and Pollino, 2012). To facilitate populating the CPTs with stakeholder-elicited probabilities, Bromley et al. (2005) use single numbers as indicative percentages. Editing information in the CPTs is straightforward and helps users raise questions and consider problems and promotes stakeholder insight (Castelletti and Soncini-Sessa, 2007). Expert knowledge and field data reconciliation is a widespread method in

constructing BBNs and populating CPTs, in which experts fill in information missing in field data (Mkrтчyan et al. 2015). Expert and stakeholder elicitation can be used to fill in CPTs when data is limited and can be updated with quantitative or qualitative data for higher model accuracy as soon as more data becomes available (Phan et al. 2016).

Parameterization methods described by Pollino et al. (2007) can serve as guidelines to develop BBNs using qualitative and quantitative data and deal with data and knowledge gaps. In constructing a BBN, it is helpful to identify the endpoint of the model first. Subsequently, variables affecting the endpoint should be identified, and arrows should connect these variables to the endpoint in the network to study the impact of the variables' change. A further hierarchy of variables indirectly conditioning the value of the endpoint can be constructed, which should include interventions and procedural decisions as management parameters. Involvement of experts and stakeholders in workshops can help in parameterizing the CPTs. A BBN framework can be developed as a starting template to use in workshops, allowing stakeholders to discuss and define variables and states on each variable. The probability derived from stakeholder perspectives can be elicited by asking "What if" questions.

The BBN should ideally be validated with data from observations and/or measurements, but when empirical information is limited, sensitivity analysis can be used to analyse the variance distribution of critical variables. For example, GeNIe BBN software has been used to analyse the sensitivity of variables influencing the reliability of drilling for kick control operation (Sule et al. 2018). In addition, discussion with experts helps to identify the robustness of variables and to consider the reasonableness of the BBN (Hoshino et al. 2016; Flores et al. 2011).

## Methodology

### BBN framework

A BBN framework was developed following the steps of Bromley et al. (2005) for designing networks through stakeholder consultation. Water-related issues were identified from secondary data and related literature and were used to establish a preliminary framework of dam planning, notably resulting in interconnected variables describing both positive and negative impacts in economic, social and environmental terms. The secondary data was taken from manuals on water resources development in Thailand. Reviews of EIA reports were performed to grasp the main criteria and data shaping positive impacts (e.g. rainfall, water storage capacity, benefits to stakeholders such as more farm income), negative impacts (e.g. deforestation, displacement of stakeholders), and mitigation measures (e.g. resettlement, compensation).

We also reviewed the concerns of affected stakeholders of dam planning in Thailand (Swain 2004), Laos (Sayatham and Suhardiman 2015), and Vietnam (Bui et al. 2013). Losing farm income is one of the crucial concerns causing conflicts in dam planning.

The preliminary framework starts with setting core contexts and defines the level of acceptance of affected stakeholders as the endpoint of negative impacts and enhanced farm income as the endpoint of beneficial outcomes. This framework connects main processes and brings in a significant number of variables from government and local stakeholders to be taken into consideration. The core government agency tasked with water resources development in Thailand is the Royal Irrigation Department (RID). The conceptualization of the generic BBN framework was presented in a meeting on 2-05-2017 to four RID officials responsible for the two studied cases to discuss and co-determine water problems, to outline the preliminary framework, and identify critical variables. The preliminary BBN framework formed the basis for workshops in both the top-down and bottom-up case studies.

### Applying the BBN framework in the case studies

The study was designed to understand the affected stakeholders' perspectives in conflict situations. Therefore, methods of stakeholder consultation outlined by Bromley et al. (2005) and parameterization by Pollino et al. (2007) were applied in the two case studies in Nakhon Si Thammarat province, Southern Thailand (Fig. 1). One case, Wang Hip, is a top-down project, where the government has set a plan to construct a medium-scale dam to supply more water to increase irrigated farmland, to produce tap water and reduce flooding in Thung Song municipality. Another case, Klong Klai, demonstrates a bottom-up approach, where the government has initiated a number of participatory meetings in search of agreed interventions to supply water for an increasing demand and to mitigate flooding, in which representatives of different villages discuss the options.

To adapt the general BBN framework to the local context, local stakeholder engagement was sought in upstream areas. Two workshops for each case were arranged in June 2017 to elicit and define the variables, their potential states, and to populate the CPTs with probabilities. "What if" questions, for example: "What are your concerns if a dam is built in the upstream area?" were asked for this purpose and, where relevant, variables were added for specific issues/concerns. Each workshop was held with ten selected participants to avoid discussions becoming excessively lengthy and repetitive. The first author acted as the workshop moderator together with a co-mediator, and four local students acted as support staff.

At the first meeting, the mediators outlined the workshop objectives and provided a basic description of BBNs to the participants. They then defined variables by discussing the preliminary framework, variables, and links. Flipcharts and post-it notes were distributed to the participants, and they were asked to write down their water problems and expectations with regard to benefits from interventions. Next, participants were asked to identify possible interventions such as dams and weirs, followed by the negative impacts that could result from those interventions—guided by "what if" questions. Hereafter, the staff collected and classified the post-it notes as groups of variables in the BBN. Subsequently, variables were grouped by economic, social, and environmental issues by the mediators. Participants were asked to focus on the negative impacts and tasked with agreeing on impact mitigation options. Following through cause and effect chains, the need for additional links between variables was considered. Questions included "Do you agree with the variables and links?", "Do you agree if variables are grouped together?", "Do you agree if this variable is added to connect those variables in terms of causes and effects?", "Do you agree to remove this variable because it is off topic?", or "Do you agree to include a link to connect these variables?". Finally, the mediators closed the first workshop by presenting a network with variables and links between them as the result of the day's deliberations. After the first meeting, the network was reviewed to align it with the general BBN framework, and some variables and links were edited. Moreover, laws and regulations for project planning were also added to the network.

The second workshop in both locations was mostly focused on understanding the CPTs for each variable. The mediators stimulated participants to discuss states, and to populate the CPTs with probabilities. To kick off the second meeting, the mediators reminded the participants of the results of the first meeting, explained what edits were made to the network, and asked for acceptance. Then the mediators asked the participants to qualify the states of every variable in simple terms, e.g. low, medium, high, or alternatively as a binary yes or no. Flipcharts and post-it notes were used as the main tools to populate the CPTs. The participants were questioned about the likelihood of events, for example, what is the possibility that a child variable will be in a particular state if the parent variables are in particular states. Through discussion, the participants reached agreement on the probability of each state. Accordingly, the probabilities of states of the child variables were established, cumulatively adding up to 100% for each child variable. The states of root variables (variables with no further parents) were populated with equal probabilities. The mediators then summarized the results and finished the session. At the end of the workshops, the mediators asked the participants to express the usefulness of the BBN workshops.

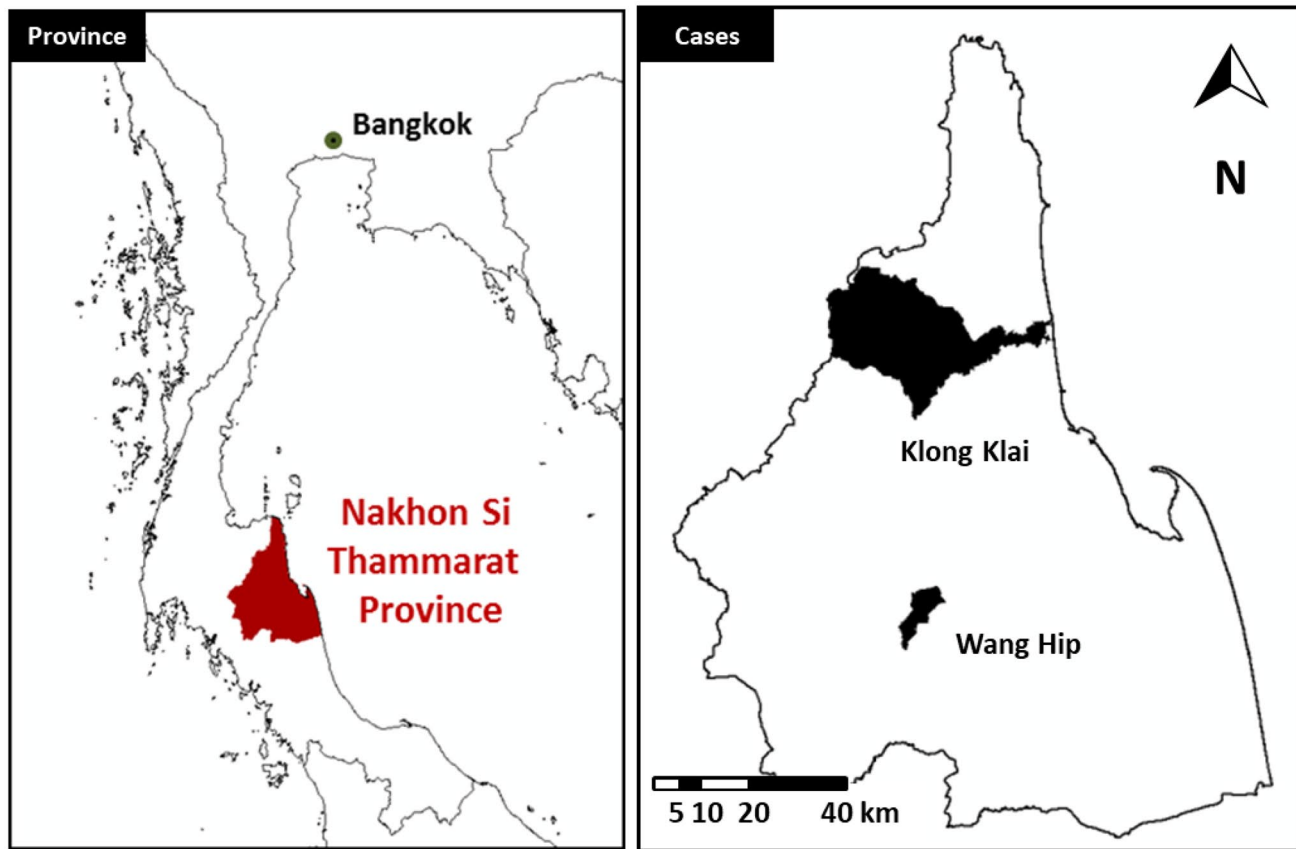


Fig. 1 Case study areas

### BBN software, sensitivity analysis and application for policy-making

The data from the two case studies were used to create BBNs using GeNIe 2.1 Bayesian software. Each variable was constructed from the start (the key water-related problems, drought and flooding, were identified from RID reports and literature, and reaffirmed in a meeting with RID officers and during the workshops with affected communities) to the alternative options for interventions, and to the end variables (more income and local acceptance), followed by inserting links between variables. The probability of impacts of a dam were computed based on local stakeholders' perspectives and concerns. We followed the manual of GeNIe Modeler (BayesFusion 2017) to run sensitivity analysis of the end variables (i.e. more income and local acceptance). We used the software to produce Tornado plots to assess how changes in influential variables effected the endpoint variable local acceptance for the case that a decision to build a dam has been made. This allowed us to verify the most important entry points for raising acceptance by affected stakeholders.

We paid particular attention to the analysis of the negative impacts of the two case studies on affected stakeholders to see if the differences in variables affected acceptance. Apart from the sensitivity analysis, the general framework and the case study results were presented to experts during September and November 2017 to understand beneficiary perspectives. In the top-down case, the BBNs were discussed during interviews with the mayor of the municipality, the deputy president of the Thung Song sub-district and the sub-district's headman as representatives of beneficiaries and local politicians, and an environmentalist who had gained the trust of affected residents and opposed the dam project. In the bottom-up case, we interviewed the president of the Krung Ching sub-district to discuss the variables and links in the BBN network.

## Results

### BBN framework

The developed BBN framework (Fig. 2) explains several features of the variables and their relations, starting

from the initiatives and following through a participatory planning process which takes stakeholders' interests and concerns regarding interventions into consideration. The outcome variables are the benefits (linked to objectives) expected from the interventions, as well as the level of acceptance by affected stakeholders experiencing negative impacts from the interventions (Table 1).

### Adaptation of the BBN framework in the case studies

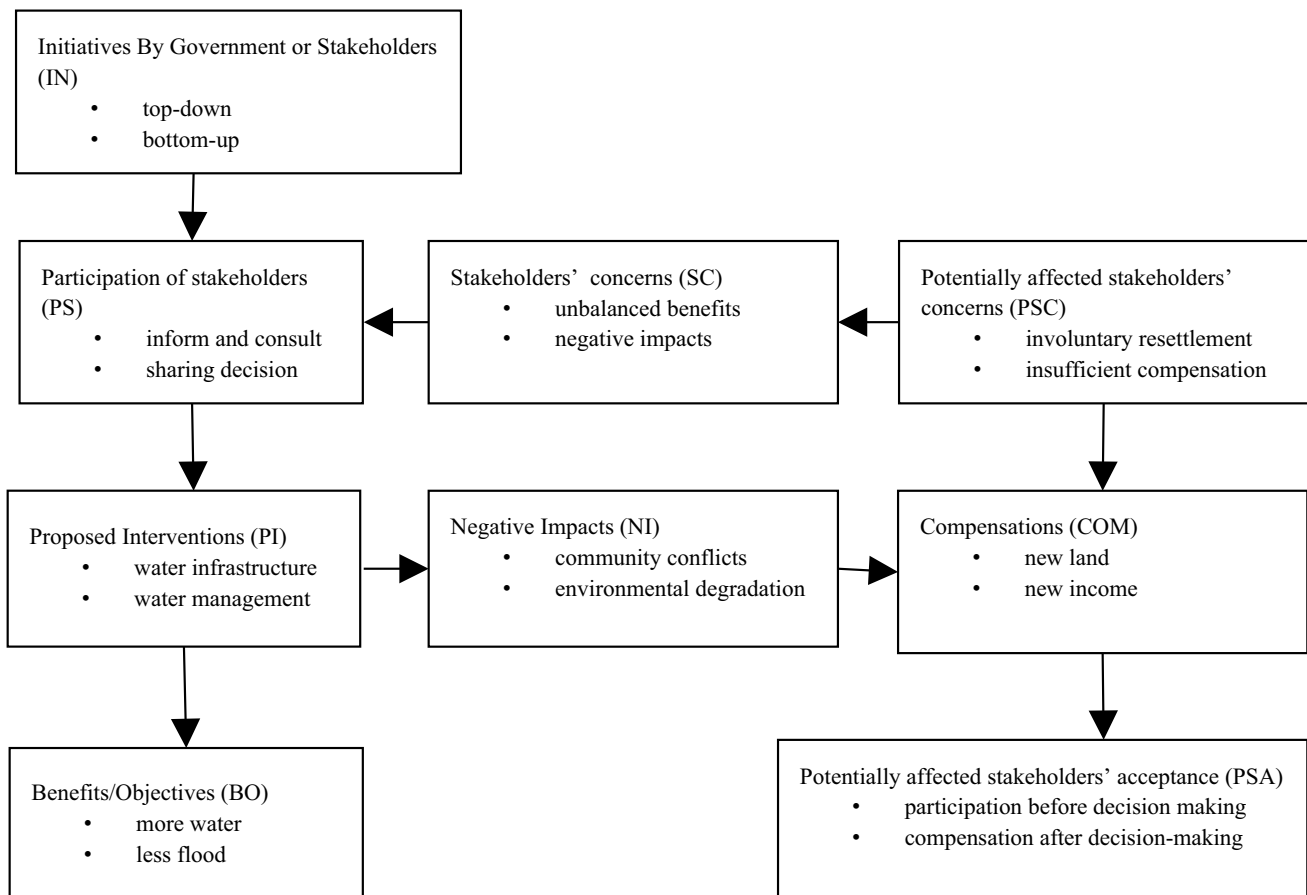
The key variables from the BBN framework are applied in two cases in Wang Hip and Klong Klai (Table 2).

#### Adaptation of the BBN framework in Wang Hip

The Wang Hip project was proposed by the government in 1990, and after a very long EIA study it was approved in 2016. The local governments at provincial, district and

sub-district levels agreed with the project moderately but did not actively promote it.

When we asked the participants to identify intervention nodes for drought problems, they proposed better water management and maintenance of existing weirs. No one mentioned the dam. But the proposed dam intervention node was raised by the facilitator to be considered and the participants agreed for the dam to be included as one of the intervention nodes so as to discuss their concerns that the dam was likely to have low influence on water problems. When presented with the BBN framework, some affected stakeholders claimed that they were not aware of some of the activities in the 'participation variable' (IM3). One of the participants stated that "the dam intervention would not have been proposed if we had been involved in the project in the early stages" (pers. comm. 13-6-2017). They provided several reasons why the dam should not have been proposed for Wang Hip, including misleading objectives. The dam (I3) was proposed as an intervention to respond to downstream water problems (P2 and P3). The participants did not believe in the links between the



**Fig. 2** Bayesian Belief Network Framework of medium-scale water resources development planning distinguishing different planning features with attention to stakeholders' concerns

**Table 1** Planning features and key elements in two case studies

Planning features	Wang Hip case	Klong Klai case
Initiatives (IN)	Top-down	Bottom-up (emerging from the process)
Participation of stakeholders (PS)	Inform	Consult
Proposed interventions (PI)	Dam	Dam, weirs, water gate
Benefits/objectives (BO)	More water for farming More water for urbanization Less flooding downtown	More water for farming Less flooding and land slides
Stakeholders' concerns (SC)	Unbalanced benefits Negative impacts	Unbalanced benefits Negative impacts Dam location
Potentially affected stakeholders' concerns (PSC)	Involuntary resettlement Insufficient compensation	Involuntary resettlement
Negative impacts (NI)	Community conflicts Environmental degradation	Community conflicts
Compensations (COM)	New land New income	Not yet discussed
Potentially affected stakeholders' acceptance (PSA)	Participation before decision making Compensation after decision-making	Participation before decision making

**Table 2** Key variables in water resources planning as derived from the BBN framework

Variables categories	Wang Hip case	Klong Klai case
Objectives	<del>O1 Seawater intrusion mitigation</del> O2 Sufficient water O3 Flood mitigation O4 Local's acceptance	O1 Seawater intrusion mitigation O2 Sufficient water O3 Flood mitigation O4 Local's acceptance
Interventions	<del>I1 Natural weirs</del> <del>I2 Water gate</del> I3 Dam	I1 Natural weirs I2 Water gate I3 Dam
Intermediate factors	<del>P1 Seawater intrusion</del> P2 Water shortage P3 Flood and landslide	P1 Seawater intrusion P2 Water shortage P3 Flood and landslide
Controlling factors	C1 Crops C2 Population C3 Rain average C4 Law and regulations	C1 Crops C2 Population C3 Rain average C4 Law and regulations
Implementation factors	IM1 Construction plan IM2 Government approval IM3 Participation IM4 Negotiation of compensation IM5 EIA <del>IM6 Dam site</del>	IM1 Construction plan IM2 Government approval IM3 Participation <del>IM4 Negotiation of compensation</del> <del>IM5 EIA</del> IM6 Dam site
Additional Impacts	A1 Promoting tourism <del>A2 Reducing sand mining</del> A3 Tap water for urbanisation	A1 Promoting tourism A2 Reducing sand mining <del>A3 Tap water for urbanisation</del>

Strike-through variables were not considered or omitted from the BBN framework

dam intervention and its objective variables and provided low probability to all objective variables (O2 and O3).

In the 'compensation variable' (IM4), the affected stakeholders mentioned that "a higher compensation rate would not contribute significantly to our acceptance" (pers. comm. 17-6-2017), which contributed to the low probability of acceptance in their 'acceptance variable' (O4). The

government pays compensation at the official land purchase rate (C4) monitored by the Land Department, which is significantly lower than market price. Moreover, official compensation rates for crops on the land are low, as rates do not consider crop yield in the long-term. Given the dominance of tree crops (rubber, durian) in the area, long lead in times

before new plantations become fully productive are a major concern to farmers.

### Sensitivity analysis for Wang Hip

The benefits of intervention are shown in Fig. 3, where the farm income variable is set as a target variable. Sensitivity analysis was performed in GeNIe to find the variables that most influence farm income. The darker red variables show highest impact on the target variable. The paler shades of red show variables with lower influence on the target variable. We found that the amount of rainfall affects the uncertainty of farm income the most. The second highest impacts are exercised by the variables 1) drought, 2) water storage and 3) irrigation water. Among these factors, rainfall is not controllable, but the rest can be partially managed by interventions or policies.

To analyse the negative impacts we set acceptance of the potentially affected villagers as the target variable (Fig. 4). The sensitivity analysis indicates that the dam construction variable and dam building policy are the most influential variables. The second most influential factor is community rights, a variable characterising the power of local stakeholders over decision-making in government projects in their area, and the third is participation in planning. This means that if the dam is constructed, it decreases the acceptance of affected households. However, paying attention to the rights of local communities and engaging affected stakeholders

in the participation process before making a decision can enhance the acceptance level. Pink variables represent the variables with less influence on acceptance, which are the variables related to compensation. The variables show that compensation can only result in a slight change in acceptance by affected stakeholders.

The sensitivity analysis (Fig. 5) shows that the affected stakeholders' acceptance is most sensitive to the decision to build the dam. This leads to uncertainty about farm income when they have to move; in particular, they fear the new land will not be productive enough to grow profitable crops. However, if the dam is definitely built, strengthening the combination of 'new farm income', 'new farm land', and 'crop price' will render acceptance less sensitive.

### Adaptations of the BBN framework in Klong Klai

The Klong Klai case describes a bottom-up water resources development approach at the river basin level. The initiative was framed by the villagers asking for some interventions. Participatory meetings at sub-district and village levels were arranged. At first, conflict was severe, but after two years of participation meetings conflict declined slightly. Stakeholders' concerns focused on the dam site location, community livelihoods, and conflict among stakeholders.

Droughts and floods were identified as the main problems and were defined as starting nodes. Then we asked

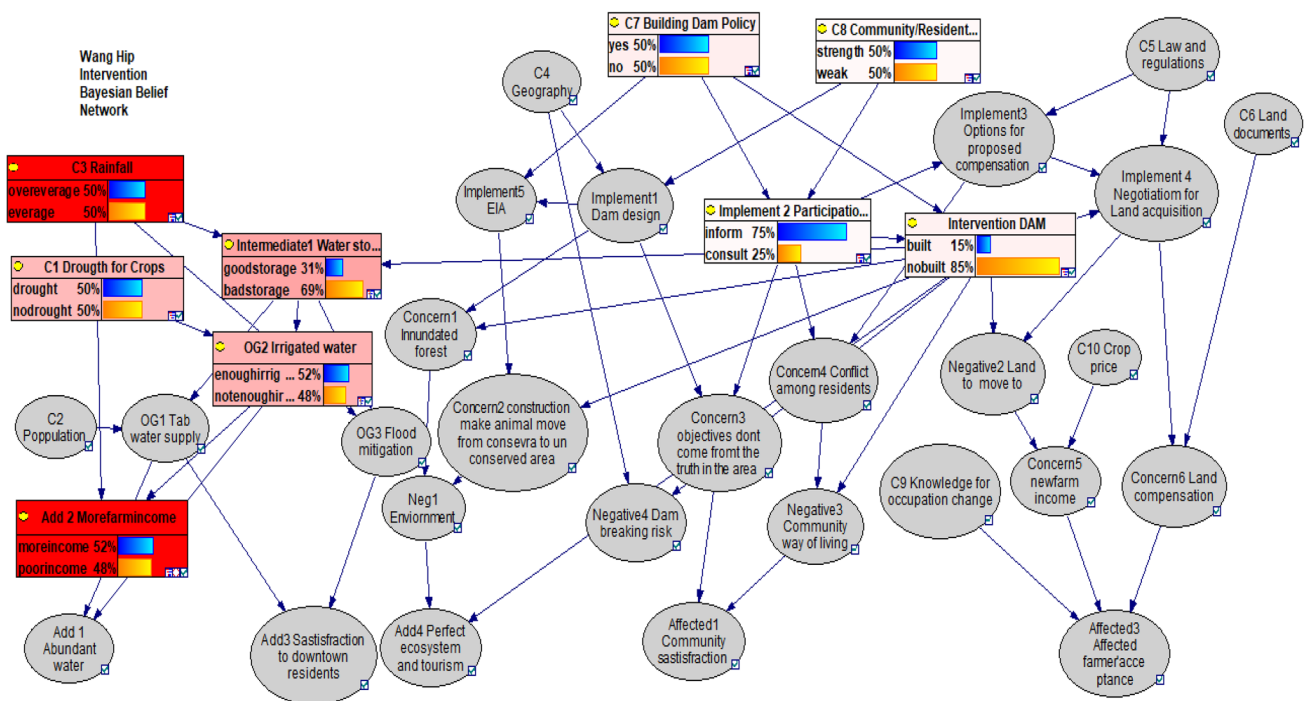


Fig. 3 The BBN and key variables for beneficial impacts of the dam in Wang Hip



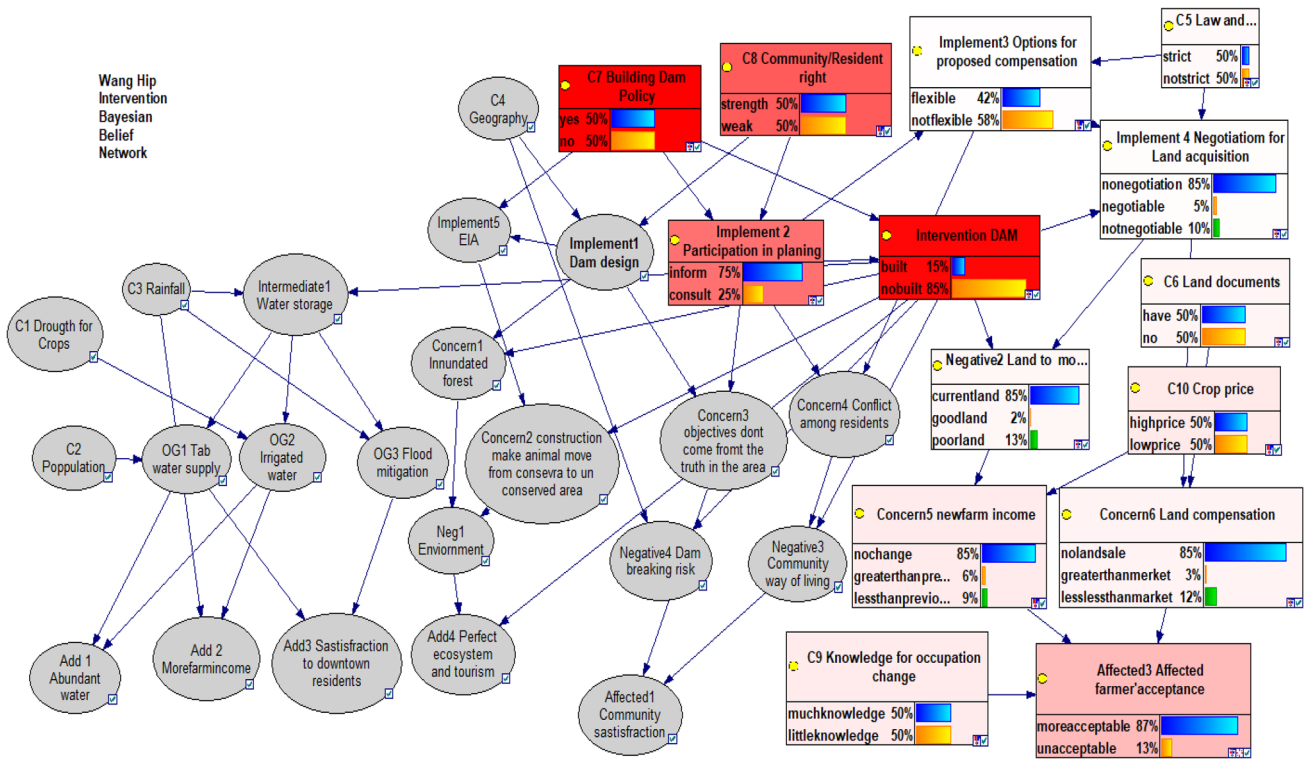


Fig. 4 The BBN and key variables for the negative impacts of the dam in Wang Hip

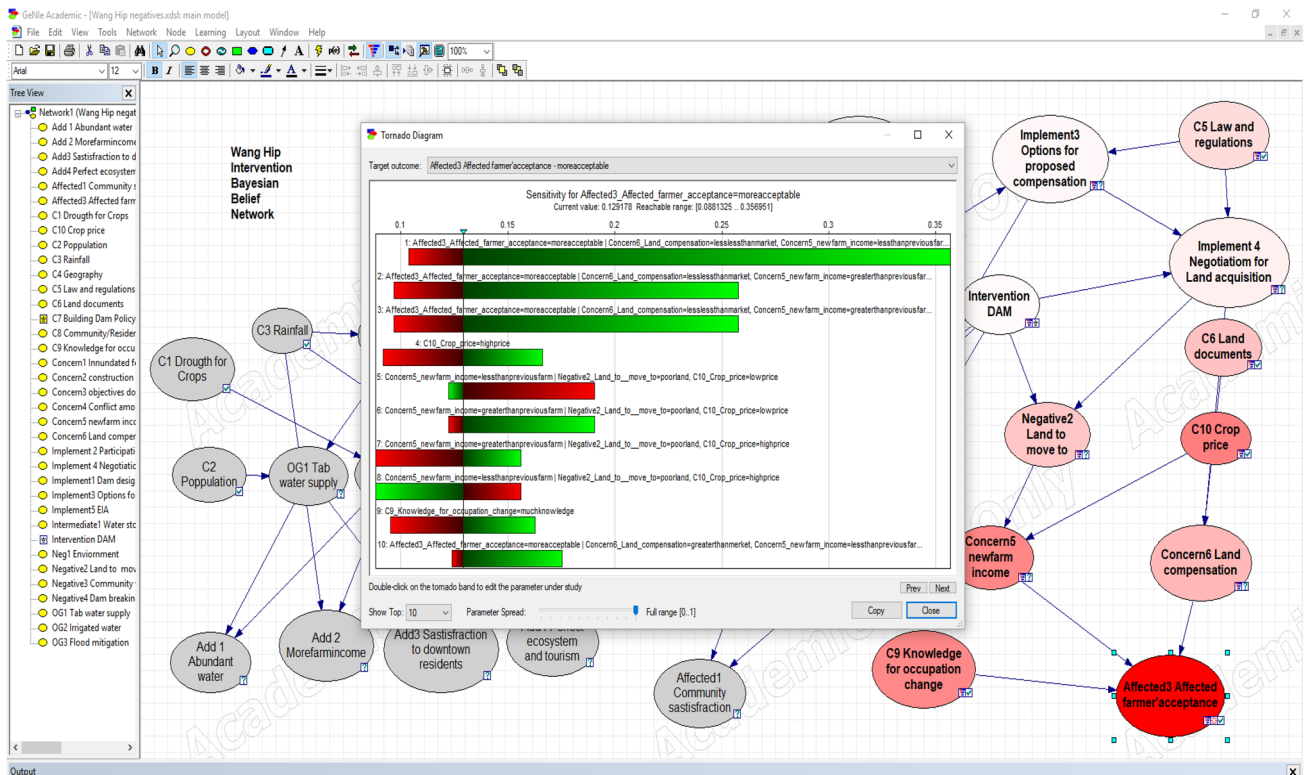


Fig. 5 Sensitivity analysis for the variables with the highest impact on local stakeholders’ acceptance in Wang Hip

participants to explain their expectations if those problems were solved; the answers pointed to increased farm income, which was set as an end node of the benefit nodes. We then asked participants to think about possible interventions to put nodes in between the problem and expectation nodes. The participants identified bamboo weirs (I1) which were built in a sub-district nearby by the community and local networks. Better water management and maintenance of existing weirs were proposed next, followed by a water gate (I2) and finally a dam (I3) was mentioned by a participant. Seawater intrusion mitigation (O1) was added as one of the objectives or benefits in the BBN, but the main aim remained to increase water storage capacity for enabling the cultivation of higher-yielding crops (C1). Local stakeholders preferred to select the dam location. So the ‘dam site’ variable (IM6) was added in the C3 workshops. The stakeholders showed uncertainty concerning livelihood options and concern that relationships within the community may be changed. The sense of community and concerns over the quality of farmland meant that they were not willing to relocate. The local stakeholders felt uncomfortable discussing compensation, saying that compensation should cover total farm income from their crops. In their opinion, the compensation rate may not be high enough to sustain their life in the long run or not enough to settle on new farmland.

### Sensitivity analysis for Klong Klai

A sensitivity analysis was performed using the GeNIe software to investigate the variables with the greatest impact on the farm income of beneficiaries and affected stakeholders’ uncertainty concerns. As shown in Fig. 6, when we set farm income as the target variable, the different shades of red show that rainfall, water reservoir, and water storage are the variables that most influence farm income. The second most important variables comprise the dam policy, drought for crops, and seawater intrusion. These variables are similar to the Wang Hip case, except seawater intrusion.

The sensitivity analysis of variables determining negative impacts on affected stakeholders shows that dam construction, government approval, and the proposed intervention by the community have the largest effect on the affected stakeholders’ acceptance (Fig. 7). The next most influential variable is the affected stakeholders’ participation in the planning process.

To analyse the sensitivity in the Klong Klai case, we used Tornado analysis (Fig. 8), assuming the dam was selected to be the only intervention in the basin, to investigate the impacts on affected stakeholders’ acceptance. We found that if we did not determine if the dam has to be built or not, the most influential variable was government approval to construct the dam (Government policy = approved). We also

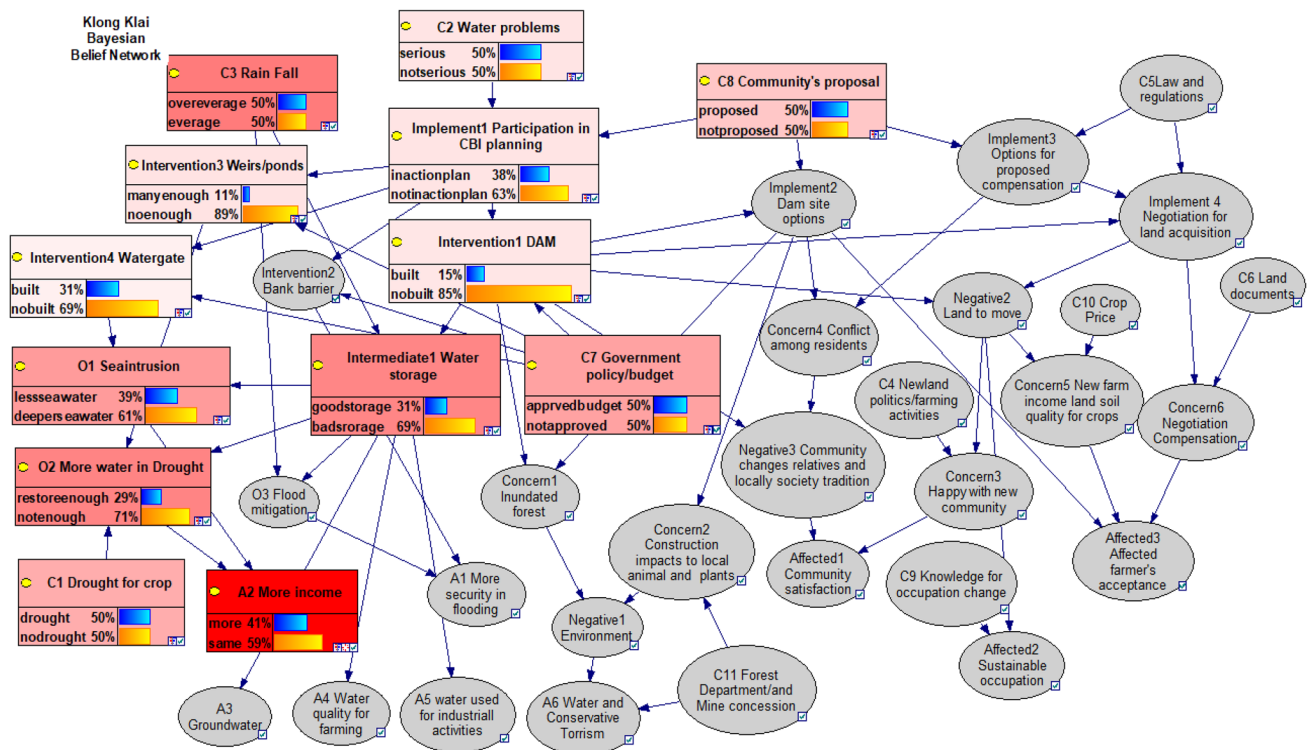


Fig. 6 The BBN and key variables for farm income benefits in Klong Klai



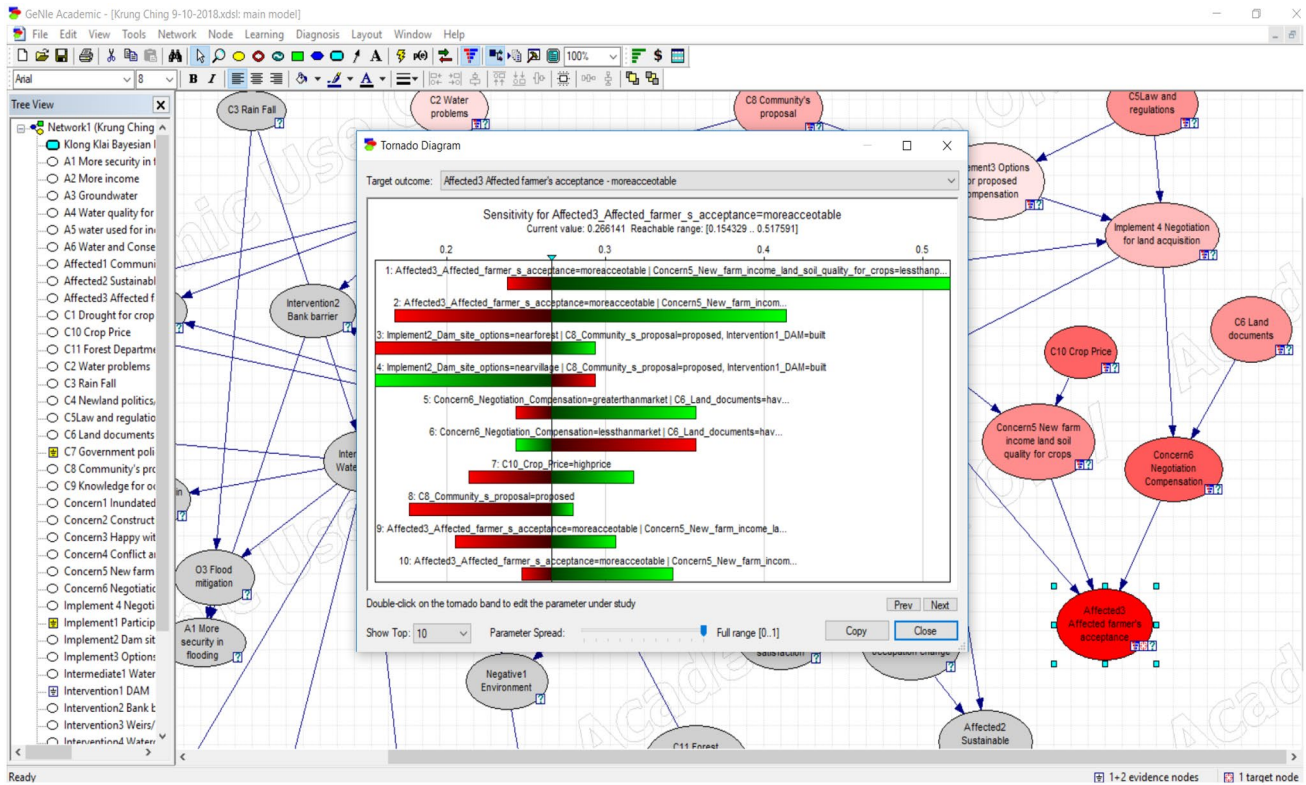
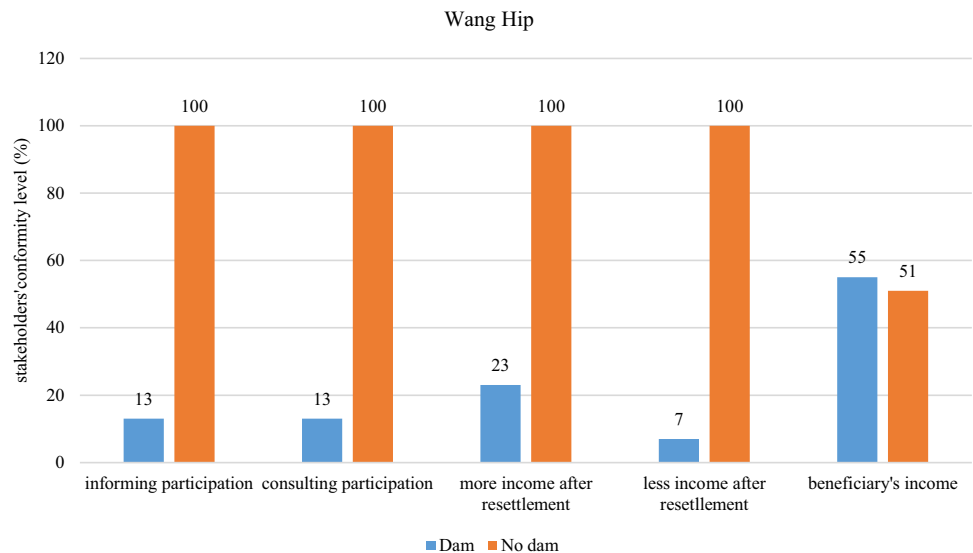


Fig. 8 Sensitivity analysis for the variables with the highest impact on the acceptance of local stakeholders in Klong Klai

Fig. 9 Wang Hip stakeholders' acceptance in response to different intervention modalities and their perceived impacts on beneficiary's income

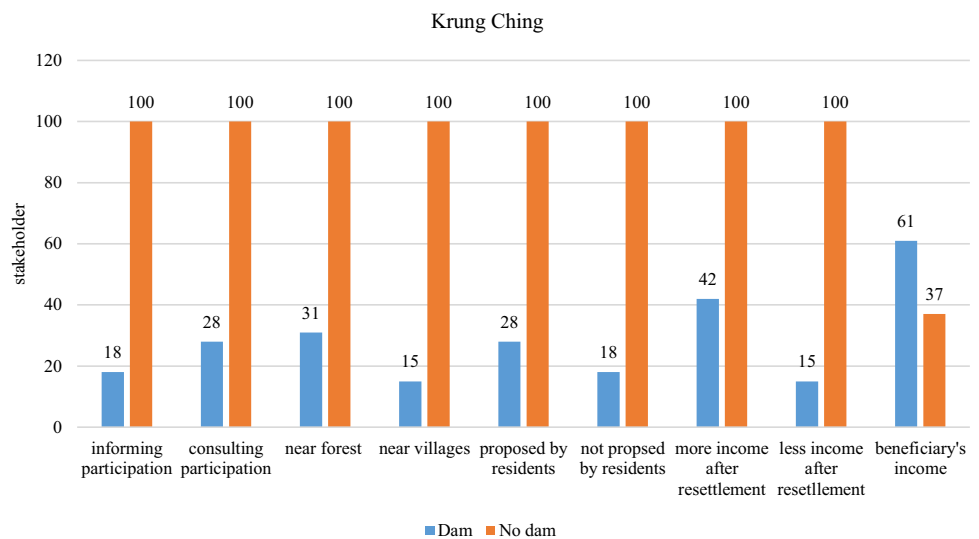


on forests, more significant than the other interventions. The local stakeholders' key concern is where to locate the dam. Stakeholder consultation during the early stages of the planning process enhanced acceptance more than restricting participation to only informing stakeholders (28% vs 18%). Constructing the dam deeper in the forest will satisfy the villagers more than constructing the dam

near the village (stakeholders' acceptance 31% vs 15%). If compensation can elevate their farm income above their current income, this will bring more acceptance by affected stakeholders (42% vs 15%).

We also presented the Klong Klai BBN results to RID officials on 18-9-2017. From the RID's environmental specialist's perspective, locating the dam in the forest raises the

**Fig. 10** Krung Ching stakeholders' acceptance in response to different intervention modalities and their perceived impacts on beneficiary's income



question as to whether the dam would have the same water storage potential as in other locations further upstream. “This question needs to be studied more in-depth in the next step, but it is good to let the local stakeholders propose the ideas, then we can negotiate” (pers.com 29-11-2017).

### The use of BBNs in building systems knowledge

The affected communities in Wang Hip saw that the BBN could foster the sustainability of development projects by highlighting critical issues to the government. The participants of the BBN workshops learned about factors for decision-making in water resource development from the variables and their links by discussing the probabilities between parent and child variables. The BBN provided a better understanding of the interaction among variables in the system. They agreed with the government attempting to solve water problems, but felt the proposed dam would not be a suitable solution in this area because water shortages and flooding were not critical. Accordingly, the participants focused on the suboptimal objectives of the projects. The dam would negatively affect the forest, the local economy and houses. There would be a higher probability that the villagers would agree with the dam if the government could solve these negative impacts, but they believed that the government could not solve all of the negative impacts.

The BBN workshops facilitated participants to put forward their concerns about the impacts of the dam on their livelihoods and helped them to define issues about which the government would need to negotiate. The process helped participants in preparing more concrete arguments to deal with the government. A participant in Wang Hip mentioned at the end of the second workshop “The workshops made us see a high possibility that the government cannot solve our problems and how we should argue to the government with

good reasons and block the government from running the project”. However, the participants also shared the concern that if the government uses a BBN in project planning for assessing the probability of acceptance, they may claim that local stakeholders agree with the dam project.

Developing the BBN allowed the villagers to share their perspectives. However, many villagers that are very critical of the dam plan did not participate in the BBN workshops. A participant in Klong Klai asserted “We enjoyed participating in the workshops even though we’ve been asked by some villagers whether we are being used by the government as a tool to build the dam”. Another participant articulated “It’s good to come to ask the villagers’ opinions and what we want, if there will be a change in the area”. However, the local stakeholders would not agree with the dam if they could not share in the benefits.

## Discussion

### Potential role of using BBNs with local stakeholders for water resources planning

BBNs can be applied in top-down and bottom-up planning processes, as BBNs can simulate outcomes from various (conflicting) angles and interests (Henriksen et al. 2007; Henriksen and Barlebo 2008). BBNs offer opportunities to define key variables and their relations taking into account the knowledge, values and interests of local stakeholders. The co-creation of one unique system of variables and their relationships enabled the participants of the workshops we held to share their knowledge and discuss their understandings of the relations between variables. Moreover, the co-created BBN was used to discuss and evaluate the estimated impacts of different alternative interventions among the

participants. Although affected stakeholders insisted on their opinions, such as not wanting a dam built, the process did catalyse their thinking about other interventions at a smaller scale such as using better water management and existing infrastructures, when the participants were asked to build intervention nodes to link between problem and expectation nodes. These suggestions may contribute to finding better solutions in a severe deadlock situation, where policymakers may see limited scope to solve water problems.

Unlike Landuyt et al. (2013), who claimed that BBNs are increasingly applied in ecosystem analysis, BBNs have barely been applied for dam planning. Our experiences show that in a conflict situation, the discussion between government planners and local stakeholders on the impacts of different intervention options by means of a BBN can support policymakers in project planning. Lynam et al. (2007) argue that BBNs outperform other models in engaging with stakeholders because of the visual way in which variables can present likelihood of impacts.

This is consistent with the argument of Carmona et al. (2013) that developing BBNs and the development of CPTs with stakeholders can help to identify possible interventions and enables stakeholders to voice their perception of the risks, challenges, negative impacts, costs and benefits of each of the proposed interventions. However, local stakeholders initially struggled to understand the probability assessment, and it took time to explain and elicit the probability for each variable, as was also reported by Henriksen et al. (2007) in a BBN study on groundwater planning.

### **Social dynamics in developing BBNs with local stakeholders**

This study focused on promoting understanding of the system and building trust among participants. A dam brings conflicts to the community because some agree while others do not. As a result, some villagers who agreed with the dam did not share their opinions to avoid arguing with neighbours. The affected stakeholders were the most crucial stakeholders, whose interests, perceptions and arguments need to be understood by policy-makers (Grimble and Wellard 1997). Prioritization of their perspectives, knowledge, values and interests may reduce conflicts during project implementation (Bal et al. 2013).

Stakeholders show distinctive perspectives on what are positive and negative impacts (Tilt and Gerkey 2016). For example, some of the potentially affected residents were afraid of living far away from their relatives while workshop participants that lived more downstream agreed with building the dam for better water management. In both top-down and bottom-up approaches, the main variables affecting the stakeholders' concerns were resettlement and insufficient compensation, which is similar to results of

other dam impact studies (Bui et al. 2013; Sayatham and Suhardiman 2015). When confronted with resettlement, potentially affected stakeholders raised issues of ecological problems as key reasons for opposition against dam projects.

Comparison of the BBN variables in the case studies shows that the top-down and bottom-up processes led to different variable selections. In the bottom-up approach, the assessment of water resources was more exploratory, and as a consequence there was a larger variety of objectives and of intervention options being assessed. However, as the stakeholders consulted were village representatives, they focused on issues and interventions that were of interest from a local stakeholder perspective, and did not consider other demands for water for e.g. industrial development. On the other hand, the top-down approach led to a narrow assessment of objectives in line with a predefined planned intervention. This left little room to consider alternative interventions and other impacts. While Bromley et al. (2005) state that BBN can combine all variables related to equity, sustainability, and efficiency, it is important to notice that in both cases presented here, some sensitive variables were left out of the BBNs i.e. displacement and compensation. In the bottom-up approach, government actors avoided talking about potential levels of compensation to prevent creating a strong opposition in the early planning period. Similarly, local stakeholders did not raise the subject of environmental issues. While they discussed that moving the dam location upstream would solve the social impacts for affected stakeholders, they did not consider that this location in the protected forest area could have serious environmental implications. The EIA may not be approved by the government departments that are responsible for forest area protection for water sources and wildlife habitats. In the top-down case, policymakers initially focused more on economic development benefits for downstream stakeholders and paid less attention to upstream stakeholders affected by the dam. Reed (2008) suggests that all important issues need to be considered from the beginning. In our cases, characterised by strong conflict, sensitive issues such as a dam intervention were not raised by the participants. Although Lynam et al. (2007) caution that facilitators should not disrupt unexpected results, we followed Reed's (2008) advice and raised the issue of the dam so that it could be discussed in this participatory platform. By creating BBNs, these sensitive variables can be put in the network and linked to other related variables so that all important impacts of interventions are addressed. It is hence important to verify that such sensitive variables are not overlooked.

Sensitivity analysis can test the robustness of the outcomes to the state of related variables in a BBN, provided that a single target node is investigated. The acceptance by local stakeholders was set as the target node for the sensitivity analysis in our cases. The Tornado plots resulting from

the sensitivity analysis contributed to developing interventions and policies for mitigating conflicts in dam planning. This correspond Kjaerulf and van der Gaag (2000) and Sule et al. (2018) who found that the BBN sensitivity analysis was of practical use to understand how a single target outcome was influenced by various variables and hence helped to direct interventions to those with the largest influence, respectively for medical and environmental management cases.

## Conclusion

A BBN framework for water resources development was constructed based on a review of policy documents and context and applied in two cases in Southern Thailand characterised by conflicts over water resources and incomplete data.

In the first case, with bottom-up assessment of water resources planning, the BBN framework was effective in stimulating stakeholders to see the positives and negatives from different options for water resources interventions. Villagers found common ground in selecting variables and completing CPTs. BBNs proved capable of directly and indirectly linking all factors in a way that was easy for them to understand. The villagers could also understand other stakeholders' interests, opening up opportunities to negotiate solutions and sharing of benefits and impacts.

In the top-down case, the potentially affected villagers opposed the dam and did not want to negotiate compensation. Their concerns were mostly about the uncertainty of finding new productive farmland for resettlement. Therefore, higher land compensation could be an option, although higher compensation only provided marginally higher levels of acceptance in the two cases.

Based on the two case studies, we can conclude that to increase the level of acceptance and reduce conflicts, the government should pay more attention to sharing decision power through participation before making decisions; and after making a decision, increase compensation rates, assist in finding good quality farmland, and show more concern for community livelihoods.

This study contributes a method to better understand affected stakeholders' concerns about water development projects and identify ways to take their perspectives into consideration in the planning process to increase their acceptance of the outcomes. By focussing on the affected stakeholders' perspectives, the BBN development process became about giving these stakeholders a voice and getting their perspectives heard.

Policy-makers involved in water resources planning should adopt elicitation methods that allow affected stakeholders to provide their system understanding (such as the

BBNs in this study) and use the predicted outcomes of the model to find more acceptable solutions, and/or to better inform communities about planned projects, e.g. through presenting benefits and impacts in a whole system diagram including dynamic relations among them. Moreover, policy-makers should apply BBNs in consulting and negotiating over acceptable solutions in early dam planning stages for equitable benefit-sharing.

The BBN framework can be adapted to other cases, and could also be used to integrate the perspectives of different stakeholders. By considering different types of data e.g. quantitative and qualitative data, the models could be further developed and, to some extent, validated. While the current study did not attempt this, the study was instrumental in helping planners to take the emerging sensitivities into account in the decision-making process by putting more effort into the specific issues of conflict. A new insight of this study is that the elicitation of local knowledge and perceptions with specific attention to local stakeholders in conflict situations helped building trust while creating the BBN.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no competing interests.

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## References

- Baillergeau E, Duyvendak JW (2016) Experiential knowledge as a resource for coping with uncertainty: evidence and examples from the Netherlands. *Health Risk Soc* 18(7–8):407–426
- Bal M, Bryde D, Fearon D, Ochieng E (2013) Stakeholder engagement: achieving sustainability in the construction sector. *Sustainability* 5(2):695–710
- BayesFusion LLC (2017) GeNIe Modeler—User Manual. BayesFusion, LLC, p 524

- Bertone E, Sahin O, Richards R, Roiko A (2016) Extreme events, water quality and health: a participatory Bayesian risk assessment tool for managers of reservoirs. *J Clean Prod* 135:657–667
- Bouejla A, Chaze X, Guarnieri F, Napoli A (2014) A Bayesian network to manage risks of maritime piracy against offshore oil fields. *Saf Sci* 68:222–230
- Bromley J, Jackson NA, Clymer O, Giacomello AM, Jensen FV (2005) The use of Hugin® to develop Bayesian networks as an aid to integrated water resource planning. *Environ Model Softw* 20(2):231–242
- Bui TMH, Schreinemachers P, Berger T (2013) Hydropower development in Vietnam: Involuntary resettlement and factors enabling rehabilitation. *Land Use Policy* 31:536–544
- Cain J (2001) Planning improvements in natural resource management. guidelines for using bayesian networks to support the planning and management of development programmes in the water sector and beyond. Centre Ecol Hydrol
- Carmona G, Varela-Ortega C, Bromley J (2011) The use of participatory object-oriented Bayesian networks and agro-economic models for groundwater management in Spain. *Water Resour Manage* 25(5):1509–1524
- Carmona G, Varela-Ortega C, Bromley J (2013) Participatory modelling to support decision making in water management under uncertainty: two comparative case studies in the Guadiana river basin, Spain. *J Environ Manage* 128:400–412
- Castelletti A, Soncini-Sessa R (2007) Bayesian Networks and participatory modelling in water resource management. *Environ Model Softw* 22(8):1075–1088
- Chen SH, Pollino CA (2012) Good practice in Bayesian network modelling. *Environ Model Softw* 37:134–145
- Devitt P, Hitchcock RK (2010) Who drives resettlement? The case of Lesotho's Mohale Dam
- Duarte-Abadía B, Boelens R, Roa-Avenidaño T (2015) Hydropower, encroachment and the re-patterning of hydrosocial territory: the case of Hidrosogamoso in Colombia. *Hum Organ* 74(3):243–254
- Farmani R, Henriksen HJ, Savic D (2009) An evolutionary Bayesian belief network methodology for optimum management of groundwater contamination. *Environ Model Softw* 24(3):303–310
- Flores MJ, Nicholson AE, Brunskill A, Korb KB, Mascaro S (2011) Incorporating expert knowledge when learning Bayesian network structure: a medical case study. *Artif Intell Med* 53(3):181–204
- Grimble R, Wellard K (1997) Stakeholder methodologies in natural resource management: a review of principles, contexts, experiences and opportunities. *Agric Syst* 55(2):173–193
- Henriksen HJ, Barlebo HC (2008) Reflections on the use of Bayesian belief networks for adaptive management. *J Environ Manage* 88(4):1025–1036
- Henriksen HJ, Rasmussen P, Brandt G, Von Buelow D, Jensen FV (2007) Public participation modelling using Bayesian networks in management of groundwater contamination. *Environ Model Softw* 22(8):1101–1113
- Hoshino E, van Putten I, Girsang W, Resosudarmo BP, Yamazaki S (2016) A Bayesian belief network model for community-based coastal resource management in the Kei Islands, Indonesia. *Ecol Soc* 21(2)
- Julian DA, Reischl TM, Carrick RV, Katrenich C (1997) Citizen participation—lessons from a local United Way planning process. *J Am Plan Assoc* 63(3):345–355
- Keshtkar A, Salajegheh A, Sadoddin A, Allan MG (2013) Application of Bayesian networks for sustainability assessment in catchment modeling and management (Case study: the Hablehrood river catchment). *Ecol Model* 268:48–54
- Kjærulff U, van der Gaag LC (2000) Making sensitivity analysis computationally efficient. In: Proceedings of the sixteenth conference on uncertainty in artificial intelligence. Morgan Kaufmann Publishers Inc., pp 317–325
- Landuyt D, Broekx S, D'hondt R, Engelen G, Aertsens J, Goethals PL (2013) A review of Bayesian belief networks in ecosystem service modelling. *Environ Model Softw* 46:1–11
- Levontin P, Kulmala S, Haapasaari P, Kuikka S (2011) Integration of biological, economic, and sociological knowledge by Bayesian belief networks: the interdisciplinary evaluation of potential management plans for Baltic salmon. *ICES J Mar Sci* 68(3):632–638
- Lynam T, De Jong W, Sheil D, Kusumanto T, Evans K (2007) A review of tools for incorporating community knowledge, preferences, and values into decision making in natural resources management. *Ecol Soc* 12(1)
- Mahato BK, Ogunlana SO (2011) Conflict dynamics in a dam construction project: a case study. *Built Environ Project Asset Manag* 1(2):176–194
- Mamitimin Y, Feike T, Doluschitz R (2015) Bayesian network modeling to improve water pricing practices in northwest China. *Water* 7(10):5617–5637
- Marcot BG, Steventon JD, Sutherland GD, McCann RK (2006) Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. *Can J For Res* 36(12):3063–3074
- Mkrtchyan L, Podofillini L, Dang VN (2015) Bayesian belief networks for human reliability analysis: a review of applications and gaps. *Reliab Eng Syst Saf* 139:1–16
- Phan TD, Smart JC, Capon SJ, Hadwen WL, Sahin O (2016) Applications of Bayesian belief networks in water resource management: a systematic review. *Environ Model Softw* 85:98–111
- Pollino CA, Woodberry O, Nicholson A, Korb K, Hart BT (2007) Parameterisation and evaluation of a Bayesian network for use in an ecological risk assessment. *Environ Model Softw* 22(8):1140–1152
- Reed MS (2008) Stakeholder participation for environmental management: a literature review. *Biol Cons* 141(10):2417–2431
- Ridder D, Pahl-Wostl C (2005) Participatory integrated assessment in local level planning. *Reg Environ Change* 5(4):188–196
- Roobzahani A, Ebrahimi E, Banihabib ME (2018) A framework for ground water management based on bayesian network and MCDM techniques. *Water Resour Manage* 32(15):4985–5005
- Sayatham M, Suhardiman D (2015) Hydropower resettlement and livelihood adaptation: the Nam Mang 3 project in Laos. *Water Resour Rural Dev* 5:17–30
- Singer J, Pham HT, Hoang H (2014) Broadening stakeholder participation to improve outcomes for dam-forced resettlement in Vietnam. *Water Resour Rural Dev* 4:85–103
- Singto C, Fleskens L, Vos J (2018) Institutionalizing participation in water resource development: bottom-up and top-down practices in southern Thailand. *Water* 10(6):781
- Sule I, Khan F, Butt S, Yang M (2018) Kick control reliability analysis of managed pressure drilling operation. *J Loss Prev Process Ind* 52:7–20
- Swain A (2004) Political structure and dam conflicts: comparing cases in Southeast Asia
- Ticehurst JL, Newham LT, Rissik D, Letcher RA, Jakeman AJ (2007) A Bayesian network approach for assessing the sustainability of coastal lakes in New South Wales Australia. *Environ Model Softw* 22(8):1129–1139
- Tilt B, Gerkey D (2016) Dams and population displacement on China's Upper Mekong River: implications for social capital and social-ecological resilience. *Global Environ Change* 36:153–162
- van Asselt MBA, Rijkens-Klomp N (2002) A look in the mirror: reflection on participation in integrated assessment from a methodological perspective. *Global Environ Change* 12(3):167–184



Xue J, Gui D, Lei J, Zeng F, Mao D, Zhang Z (2017) Model development of a participatory Bayesian network for coupling ecosystem services into integrated water resources management. *J Hydrol* 554:50–65

Zorrilla P, Carmona G, De la Hera Á, Varela-Ortega C, Martínez-Santos P, Bromley J, Henriksen HJ (2010) Evaluation of Bayesian networks

in participatory water resources management, Upper Guadiana Basin, Spain. *Ecol Soc* 15(3)

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