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A methodological framework to support the initiation, design and institutionalization of participatory modeling processes in water resources management

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ABSTRACT

Multiple barriers constrain the widespread application of participatory methods in water management, including the more technical focus of most water agencies, additional cost and time requirements for stakeholder involvement, as well as institutional structures that impede collaborative management. This paper presents a stepwise methodological framework that addresses the challenges of context-sensitive initiation, design and institutionalization of participatory modeling processes. The methodological framework consists of five successive stages: (1) problem framing and stakeholder analysis, (2) process design, (3) individual modeling, (4) group model building, and (5) institutionalized participatory modeling. The Management and Transition Framework is used for problem diagnosis (Stage One), context-sensitive process design (Stage Two) and analysis of requirements for the institutionalization of participatory water management (Stage Five). Conceptual modeling is used to initiate participatory modeling processes (Stage Three) and ensure a high compatibility with quantitative modeling approaches (Stage Four). This paper describes the proposed participatory model building (PMB) framework and provides a case study of its application in Québec, Canada. The results of the Québec study demonstrate the applicability of the PMB framework for initiating and designing participatory model building processes and analyzing barriers towards institutionalization.

1. Introduction

Water legislation such as the U.S. Clean Water Act, the Québec Water Policy and the European Water Framework Directive emphasize the need for integrated and participatory approaches for the sustainable management of water resources. Participatory modeling has been found to be a useful methodology to support stakeholder involvement and integrated analysis of water resources issues (e.g., Pahl-Wostl et al., 2007; Serrat-Capdevila et al., 2011; Inam et al., 2015). Stakeholders can be an individual or group who can (indirectly or directly) affect or be affected by an issue or a topic of interest (Glicken, 2000), such as a water quality issue. By building a model, stakeholders can express their points of view, learn about other perspectives, and examine factual knowledge and subjective perceptions (Pahl-Wostl, 2007). The construction of simulation models allows for the testing of assumptions and thereby supports learning about the system (Dörner, 1996; Sterman, 2000).

There are profound barriers to the implementation of participatory modeling in water resources management. First, the initiation of participatory modeling processes is often hampered due to the limited modeling and facilitation skills of practitioners (e.g., water agencies) (Hare, 2011), and the widespread perception that stakeholder involvement is a time-consuming and costly process, while the benefits remain obscure (Morrison, 2003; Winz et al., 2009; Hare, 2011). Second, context-specific design of participatory modeling processes is a challenging task and requires methodological development to adapt the process to physical, environmental, socio-economic and institutional circumstances (Hatzilacou et al., 2007; Winz et al., 2009; Metcalf et al., 2010). Besides a context-

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specific customization, an explicit process design also allows for a rigorous monitoring and evaluation of participatory modeling processes by specifying process steps and intended outcomes (see Jones et al., 2009; Carr et al., 2012). Third, participatory modeling processes are often constrained to short and mid-term 'interventions' during research projects led by modeling experts (Voinov and Bousquet, 2010), even though significant improvement of water issues usually requires long-term engagement (Pahl-Wostl et al., 2007). Thus, approaches are needed that support an analysis of requirements for long-term participatory modeling processes which involve envisioning of supportive institutional structures and mechanisms for capacity building.

This paper proposes a participatory model building (PMB) framework that addresses the aforementioned challenges by proposing an innovative stepwise approach for the *initiation*, *design* and *institutionalization* of participatory modeling processes. The methodological framework consists of five successive stages: (1) problem framing and stakeholder analysis, (2) process design, (3) individual modeling, (4) group model building, and (5) institutionalized participatory modeling. The PMB framework combines context-sensitive process design (Stages One and Two), a focus on process initiation through a low-threshold modeling approach (Stage Three), a high compatibility with quantitative modeling approaches (in Stage Four), and an analysis of requirements for institutionalized participatory modeling (Stage Five).

The structure of the paper is as follows. First, the methodological foundations of the PMB framework are introduced including the Management and Transition Framework (MTF), as well as conceptual participatory modeling. Second, the five steps of the PMB framework and their links to other participatory modeling frameworks are presented. Third, a case study in Québec, Canada, on water quality management is provided, in which the application of the PMB framework is tested and assessed. Our experiences from the case study in Québec and further participatory modeling processes in Ontario (Canada), Cyprus, Guatemala and Pakistan are discussed, before we conclude with suggestions for future research.

2. Methodological background

The MTF and conceptual participatory modeling are the methodological foundations of the PMB framework. The MTF is used for problem and stakeholder analysis (Stage One), context-sensitive process design (Stage Two) and analysis of requirements for institutionalized participatory modeling (Stage Five). Conceptual modeling is used to initiate participatory modeling processes (Stage Three) and ensure a high compatibility with quantitative modeling approaches (Stage Four).

2.1. Management and transition framework

The MTF was developed by Pahl-Wostl et al. (Pahl-Wostl et al., 2010; Knieper et al., 2010; Pahl-Wostl, 2015; Knüppe and Knieper, 2016) as a diagnostic tool for water resources governance and management problems. The MTF is based upon the three conceptual pillars of adaptive management (e.g., Holling, 1978), social learning and transformation processes (Pahl-Wostl et al., 2007), as well as the Institutional Analysis and Development Framework (Ostrom, 2005). Key concepts and their relationships are specified through a class diagram that defines the general structure of a water system (Fig. 1a). Each class (e.g., 'technical infrastructure' or 'actor') is characterized by certain attributes that allow for a detailed description of case-specific conditions (for instance, actors can be characterized by sectors and the spatial scale at which they typically operate). Relational databases are used to support formalization and standardization of data collection and representation (Knieper et al., 2010).

The overarching problem boundaries are given by the 'Water System' which comprises all environmental and human components (Fig. 1a). The 'Ecological System' class comprises abiotic and biotic components of the water system, which provide different services for human activities. The 'Societal System' embeds multiple 'Action Arenas', which are issue-specific political arenas focused on a societal function such as flood protection or water supply, and characterized by 'Strategic Management Goals', 'Actors' and 'Action Situations'. An 'Action Situation' is a key concept of the MTF that allows for the analysis of the water management process and is defined as a structured social interaction context that leads to specific outcomes (see Fig. 1b). Results of an action situation can be, for example, institutions or knowledge which can affect social interactions in other action situations, or direct physical interventions in the system such as implementation of infrastructure or distribution of water to different uses.

Thus, the MTF is able to specify (a) the overall structure of the water system which forms the context in which management processes take place (Fig. 1a), as well as (b) water management processes as a sequence of action situations including influencing factors and outputs (Fig. 1b). As depicted in Fig. 1a, the MTF has a number of other classes (e.g. institution, knowledge, role), which are explained in detail in Pahl-Wostl et al. (2010) and Pahl-Wostl (2015).

The application of the MTF as a diagnostic, ex-post analysis tool has been extended in the PMB Framework towards a planning, ex-ante analysis tool (see Sections 3.2 and 3.5 for a detailed explanation). The MTF allows for the systematic examination and graphical representation of the process steps, as well as interactions between context and process, which includes the definition of action situations, participating actors, and aspired outcomes (Halbe et al., 2013). In addition to its application for problem diagnosis and process design, the MTF is also applied for the analysis of requirements for institutionalizing participatory modeling. Here, institutionalization is understood as "cognitive, normative, and regulative structures and activities that provide stability and meaning to social behavior" (Scott, 1995, p. 33). The institutionalization of the participatory model building process comprises the development of the capacity of stakeholders (e.g., water agencies) to continue the participatory modeling process in the long-term (i.e., *cognitive activities* such as the development of modeling skills), awareness raising for the relevance of stakeholder involvement in civic, professional and political networks (i.e., *normative activities* such as curriculum or guideline development), and the establishment of formal rules to organize the process and specify its mandate (i.e., *regulative activities/structures* such as mechanisms for conflict resolution and implementation).

2.2. Conceptual participatory modeling

Participatory modeling involves the engagement of stakeholders in the modeling process, which can be accomplished in various forms, ranging from direct participation in model construction to consultation on model validity and testing of a completed simulation model (Hare, 2011). Beall and Ford (2010) define three continuums that illustrate the diversity in participatory environmental modeling: (1) The "hands on continuum" that ranges from models built by experts with some input of participants to joint problem mapping with participants; (2) the "problem definition to solution producing continuum" that points to the complexity that is addressed in the modeling process ranging from well-defined problems and options for solutions to poorly defined "messy" problems; and (3) the "quantitative to qualitative data" continuum that expresses the various types of data that is relevant for a

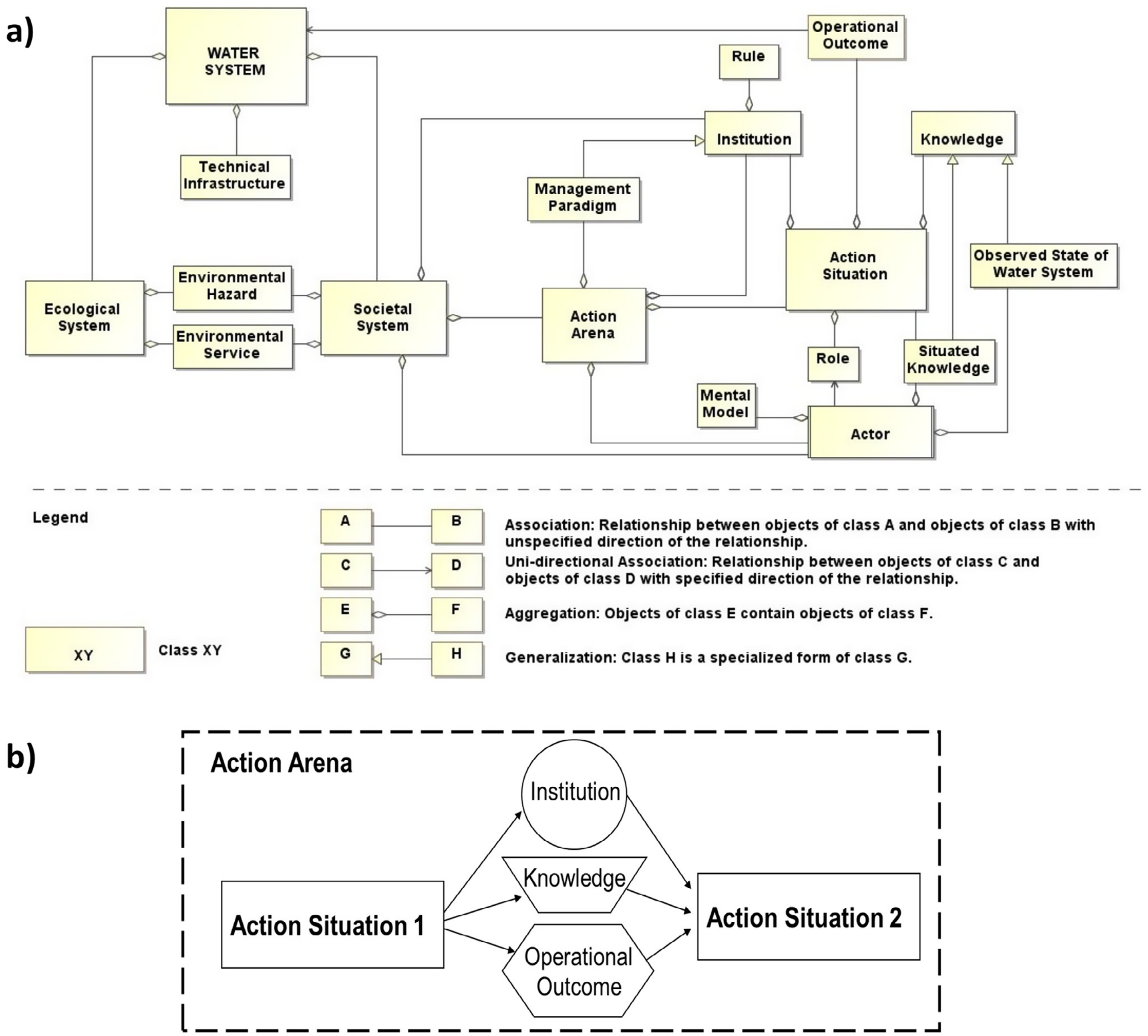

Fig. 1. (a) Class diagram in Unified Modeling Language (UML), which is part of the Management and Transition Framework, for the analysis of structural elements of the water system (slightly modified from Fig. 1 in Pahl-Wostl et al., 2010, p. 575). (b) Representation of policy and learning processes as a sequence of action situations that are embedded in an action arena and connected by institutions, knowledge and operational outcomes.

specific problem and thus needs to be included in the model, ranging from hard, quantitative data (e.g., water quality indicators) to soft, qualitative data requirements (e.g., environmental awareness).

Various participatory modeling frameworks exist that propose specific process steps and combinations of qualitative and quantitative modeling methods. Voinov and Bousquet (2010) provide an overview of different stakeholder-based modeling frameworks and criticize the proliferation of participatory modeling frameworks which in many cases only differ slightly. Major differences among existing participatory modeling frameworks relate to the modeling methods included, such as agent-based modeling (e.g., Gurung et al., 2006) or system dynamics modeling (e.g., Langsdale et al., 2006). For example, companion modeling is a well-known participatory modeling framework that integrates the application of role playing games and agent based models (e.g., Barreteau et al., 2003; Gurung et al., 2006; Campo et al., 2010). System dynamics is applied in various modeling frameworks including group model building (Vennix, 1996), mediated modeling (van den Belt, 2004) and Shared Vision Planning (Palmer et al., 2013).

Conceptual modeling is an important step in any model building process (Gupta et al., 2012), and is particularly suitable for the initiation of participatory modeling processes (Inam et al., 2015). In contrast to quantitative models, conceptual models describe system elements and their interactions in a verbal or pictorial form, often without rigorously specifying the relationships between system elements (Gupta et al., 2012). In this respect, systems thinking using causal loop diagrams (CLDs) allows for user-friendly and participatory conceptual modeling (Mirchi et al., 2012). In CLDs, elements of the system are connected by arrows and together form causal chains (for an example see Fig. 4). A positive link indicates the parallel behavior of variables: in the case of an increase in the causing variable, the variable that is affected also increases, while a decrease in the causing variable implies a decrease in the affected variable. A negative link indicates an inverse relation between variables. Feedback loops are a further central concept in systems thinking. Two different feedback loops exist that can be detected in CLDs: the self-correcting 'balancing loop' (uneven number of negative links within the loop) and the self-amplifying 'reinforcing loop' (even number of negative links) (Sterman, 2000). Causal loop diagrams built by individuals or groups represent individual or collective cognitive maps regarding a problem (e.g., water pollution or flooding). Such "a cognitive map can provide the basis for any type of advanced modeling" (van Kouwen et al., 2008, p. 1143), such as system dynamics simulation models (e.g., Langsdale et al., 2006), agent-based models (e.g., Scholz, 2016), Bayesian networks (e.g., Giordano et al., 2013) or fuzzy cognitive maps (e.g., Gray et al., 2014) (see Section 3.4 for more details).

The choice for a specific modeling method or framework should be based on the purpose of the modeling process, which can be decision-support, social learning or model improvement (Hare, 2011). Various context-factors can furthermore influence method selection and process design, such as the availability of data, the level of conflict or the size of the stakeholder group (Beall and Ford, 2010; Beall King and Thornton, 2016). The coupling of stakeholder-built models with expert models, such as SAHYSMOD (Inam et al., 2017a,b), or in combination with other tools, such as spreadsheet software (Lorie and Cardwell, 2006) or individual audience response technologies (Beall King and Thornton, 2016), constitute further options to tailor the participatory process to case-specific demands, opportunities and constraints. There is also an increasing relevance of social media and web applications in participatory modeling that allow for new contexts and scales of stakeholder participation (Voinov et al., 2016). The PMB framework developed in the current study focuses on conceptual modeling using CLDs to provide a low-threshold approach to systematically engage stakeholders (see Section 3.3 for a detailed description of the modeling approach). In addition, the PMB framework allows for compatibility with other participatory modeling frameworks that use quantitative modeling and further engagement tools (see Section 3.4).

3. Participatory model building (PMB) framework

The PMB framework has been iteratively developed and applied in several study sites over six years by our research team. Several of our publications previously focused on specific parts of the framework, such as individual interviews (Halbe, 2009; Halbe et al., 2014; Inam et al., 2015), process design and analysis of institutional structures (Halbe et al., 2013; Halbe, 2016), as well as quantitative modeling using system dynamics (Halbe, 2009; Inam, 2016; Inam et al., 2017a,b). The framework was applied in several case studies, including Cyprus (water scarcity management; Halbe, 2009, Halbe et al., 2015a), Pakistan (soil salinity management, Inam et al., 2015, 2017a,b), Guatemala (food security, Malard et al., 2015), Ontario, Canada (sustainable agriculture; Halbe et al., 2014) and Québec, Canada (water quality management; Halbe and Adamowski, 2011). While individual modeling was found to be sufficient in the Cyprus case study, stakeholders in the Québec and Guatemala cases explicitly requested a group modeling process as a result of their positive experiences with individual modeling. This inspired the development and testing of the 'Group Model Building' stage (Stage Four) in the PMB framework. The Cyprus and Québec case studies furthermore underlined the importance of process design to consider potential linkages between the participatory process and formal water management. Both cases also showed several barriers towards a long-term continuation of the process, such as the availability of modeling skills and financial resources, which required structural changes in the water governance framework. This experience resulted in the usage of the MTF as an integrated planning and analysis tool in the "Process Design" stage (Stage Two) and inclusion of the "Institutionalized Participatory Modeling" stage (Stage Five) in the framework. The different stages of the PMB framework are presented in Fig. 2.

Stakeholders such as water managers can test qualitative participatory model building in the exploratory phase (Stages One to Three) even in the context of limited funding, time and expertise, and decide after these practical experiences whether a continuation of the process is useful for the specific problem situation. More resource-intensive (quantitative) participatory modeling approaches can be applied in Stage Four, which allows the PMB framework to be highly compatible with other modeling frameworks, such as Mediated modeling, Shared Vision Planning or Group Model Building. Institutionalized participation requires that water authorities (e.g., water boards, watershed organizations) are able to organize and implement participatory processes independently from external process facilitation experts in the long-term. In Stage Five, the PMB framework therefore offers a methodology for detecting barriers to participatory management, and envisioning pathways towards capacity building in water agencies and institutional change for the realization of collaborative water management. The five stages of the proposed PMB framework are described in detail below.

3.1. Stage One: problem and stakeholder analysis

In Stage One of the PMB framework, the MTF is used as a diagnostic tool that supports a systematic collection and analysis of information for the development of a preliminary problem definition and selection of key stakeholders. All available data and information regarding the water system structure is added to the MTF database by the process organizers, such as attributes of the water system (e.g., basin area, average annual discharge, population density) and technical infrastructure (e.g., scale, ownership, state of maintenance). The evolution of the water issue is defined through a sequence of action situations in the MTF (see Section 2.1). Actors involved in the history of the water issue should be included in the database as well as information on their roles (e.g., decision-maker, expert) and sectoral affiliation (e.g., agriculture, water supply). In this first stage, the main sources of information are the scientific literature dealing with the problem and other documents that reflect the opinions and interests involved (e.g. newspaper articles, reports from interest groups). In addition, informal interviews with experts and other stakeholders can provide first impressions regarding hidden conflicts and perspectives.

Based upon data and information from the problem analysis, stakeholders relevant to finding a solution to the water issue are selected. The MTF allows for the specification of several stakeholder attributes, such as their associated spatial unit (e.g., local, regional, national), interest in the resource issue, and perceived urgency. Different methods of stakeholder analysis exist (e.g., Reed et al., 2009; Stanghellini, 2010) that can be applied based upon the data in the MTF. Halbe (2009) and Inam et al. (2015) proposed a systematic stakeholder analysis approach that is applied in Stage One of the PMB framework. First, stakeholders are sorted according to their roles, such as decision makers, users, implementers/executives and experts/suppliers (European Commission, 2003), to examine any gaps in the composition. Second, stakeholders are prioritized using three attributes (power to influence the process; legitimacy to influence; and the perceived urgency for action) in order to detect those stakeholder groups that are of critical importance for an effective stakeholder process (Mitchell et al., 1997).

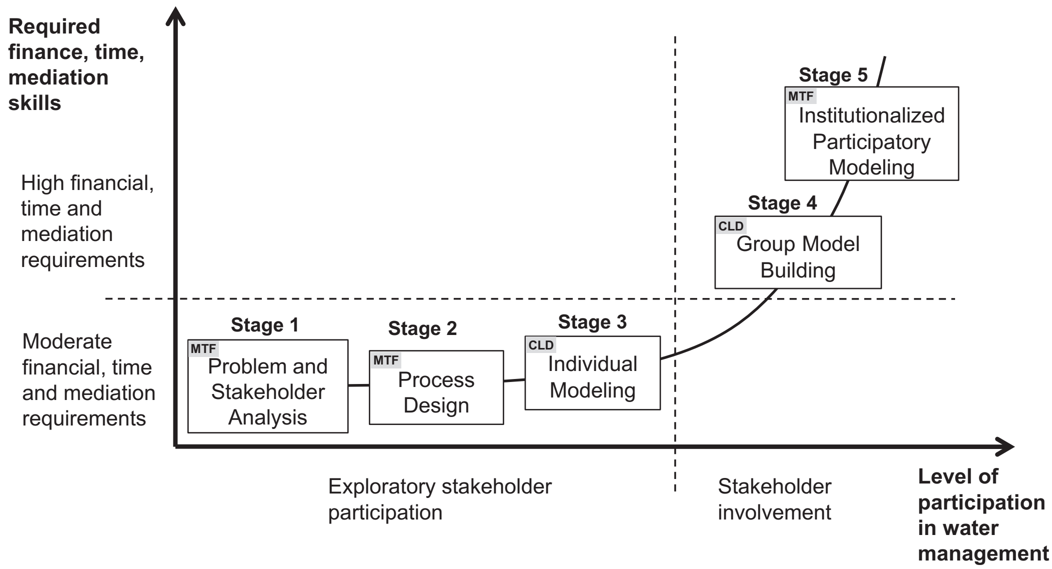

Fig. 2. The Participatory Model Building (PMB) Framework – a stepwise approach towards collaborative water management. The grey boxes show the methodological focus of the respective stage including the Management and Transition Framework (MTF) and causal loop diagrams (CLD).

3.2. Stage Two: process design

Transparent process design, a relatively young field of research (von Korff et al., 2010; Forrest and Wiek, 2014), is another important step in participatory modeling as it can prevent possible negative effects of stakeholder involvement, such as stakeholder disillusionment (Barreteau et al., 2010), lopsided decisions and increased conflict and wasted resources (von Korff et al., 2010), by clearly defining process steps and expected outcomes in advance. Process design can be guided by conceptual and methodological frameworks that define key processes and mechanisms in participatory processes (e.g., Rowe and Frewer, 2005; Barreteau et al., 2010), criteria for effective participatory modeling processes (e.g., Rouwette et al., 2002; Rowe and Frewer, 2000), and principles based upon experience from practice (e.g., von Korff et al., 2010; Argent et al., 2016).

Consideration of the context in the design of participatory processes is a critical factor (Carr et al., 2012) as institutional, socio-economic or environmental context factors can influence the outcome. Forrest and Wiek (2014) point to the need for analytical-evaluative frameworks to identify context-sensitive success factors for societal transitions towards sustainability. The MTF is such a framework which has been widely applied to analyze the embedment of water management processes in case-specific contexts (e.g., Sendzimir et al., 2010; Schlüter et al., 2010; Knüppe and Pahl-Wostl, 2012).

Process representation through action situations (see Fig. 1b, Section 2.1) is used for historical analysis of the water management processes in Stage One and the same scheme is used to plan for the organization of a future participatory process in Stage Two. Thus, each step in the participatory process is defined by an action situation (e.g., contacting potential stakeholders, organization of individual interviews) and related influencing factors and expected results (Halbe et al., 2013). The analysis of the historical process (completed in Stage One) can be used to define possible influential factors from past management efforts (e.g., a piece of legislation) as well as potential ways in which the participatory process can induce change in the water system (e.g., have a positive impact on water quality). The process planning approach using sequences of action situations allows for inclusion of stakeholders (e.g., water agencies) in the design process through a graphical representation of the process evolution over time (see Halbe et al., 2013; Halbe, 2016).

The identification of consecutive process steps allows for the definition of specific and practical process indicators, which can point to resource management outcomes (e.g., improved water quality or reduction of conflict between water users), intermediary outcomes (e.g., trust or knowledge), or process quality indicators (e.g., legitimacy of participants) (Carr et al., 2012). The continuous comparison of expected process results to actual experienced results stimulates a questioning of the applicability and suitability of the methods applied as well as underlying theories. If expectations are not met, process organizers have to rethink their understanding of the system and, based upon this, revise the organization of the participatory process (e.g., through the application of new methods and tools). Thus, the application of the MTF constitutes an important step towards effective participatory process design and evaluation (see Halbe and Ruutu, 2015).

3.3. Stage Three: individual modeling

The building of individual CLDs by each key stakeholder constitutes the third stage of the proposed PMB framework. Compared to the group modeling of Stage Four, individual interviews usually require minimal resources (i.e., only the travel costs of the facilitators) and provide an opportunity for stakeholders to express their points of view more freely, due to a personal atmosphere (i.e., only the interviewee and facilitators meet) and the absence of potential influence from other stakeholders (i.e., facilitators take a neutral position).

Three steps are proposed for the individual modeling stage of the PMB framework (Halbe, 2009; Inam et al., 2015): In the first step, facilitators visit each stakeholder that was identified in Stage One. Each stakeholder builds their CLD independently by choosing variables and drawing causal linkages. The facilitator provides only methodological support without influencing the content of the model. Variables are written on sticky notes that are put on a large sheet of paper, and causal linkages are drawn in by the stakeholders (see example model in Fig. 4). The individual modeling process begins with a discussion of the preliminary problem definition and the identification of the causes of the defined problem as well as the polarity of causal links. The consequences of the problem are then studied, and the interviewee is encouraged to find feedback loops (Vennix, 1996). Finally, solution strategies are added to the model, as well as barriers towards their implementation. In summary, this approach encourages the structured construction of a holistic system that represents the participant's mental model of the status quo as well as preferred strategies and implementation barriers. Due to its structured nature, the system thinking approach allows for the comparison of CLDs as all participants follow the same methodology (e.g., Schaffernicht and Groesser, 2011). The analysis of the causal structures furthermore supports a deep understanding of the causes, consequences and possible intervention points (Sterman 2000).

In the second step, individual CLDs are merged into an overall CLD by the facilitator to provide a holistic picture of the water issues based on the different mental models of the stakeholders. Conflicts and diverging points of views are elicited by comparing and merging CLDs built by individual stakeholders (see Inam et al., 2015 for more details on comparing and merging CLDs). The CLDs from different stakeholders may consist of redundant, complementary, or oppositional elements. Oppositional system representations should be highlighted (e.g., by an exclamation mark) since these aspects may create potential conflicts between stakeholder groups (Halbe et al., 2015a). If complementary system elements are available, the merging of these aspects will result in a more detailed model structure (Inam et al., 2015). To avoid the preparation of an unwieldy merged model (with a large number of variable names and crossing causal links), it can be useful to develop thematic models. Thematic models are clearly arranged sub-models that represent the collective viewpoint on a certain topic, such as environmental or socio-economic aspects (see Appendix A for examples of thematic models). Merging individual CLDs can be a challenging task "as interviewees may use different words for the same concept, may refer to different concepts with the same words, or use concepts that overlap but do not match exactly" (Halbe et al., 2015a, p. 6). Thus, some interpretation is needed to develop a comprehensive overall CLD model and subdivide it into thematic models. In the end, the merged model should be regarded as a preliminary group model that includes diverging stakeholder perspectives. Such a model can allow water authorities to see the potential benefits of group model building processes that will be organized in Stage Four of the PMB framework.

In the third step, the presentation of the merged CLD model to the participants aims at supporting a learning process as stakeholders examine different perspectives and ideas. A workbook can be designed that includes the merged model and a questionnaire to ask for stakeholder opinions regarding the merged model (Halbe, 2009) (see Appendix B for a workbook designed for the Québec case study).

Based upon the experiences and findings in Stages One to Three, water managers and other stakeholders can decide whether investment in more intensive stakeholder involvement (Stage Four) is sufficiently promising to address the case-specific water issues.

3.4. Stage Four: group model building

The group model building stage of the PMB framework involves the organization of group workshops in which stakeholders meet face-to-face. Such personal interactions are critical for effective social learning processes (Pahl-Wostl, 2007), and require professional conflict mediation skills (van den Belt, 2004). Compared to the individual modeling of Stage Three, group processes usually require substantial resources for renting an appropriate meeting place, supplementary material, catering and travel of stakeholders. In an acute problem situation, stakeholders might have a high motivation to participate and might bring in some of their own resources. Stakeholders with a low interest in a change of the status quo might however refuse to make an effort. The limited motivation of some stakeholders is particularly problematic for the organization of multiple workshops, which can result in low attendance and discontinuity (e.g., Videira et al., 2009; Burgin et al., 2013).

Conceptual modeling helps to develop a common understanding of how a system works, and thus supports communication and learning between modelers, decision makers and other stakeholders (e.g., Liu et al., 2008; Serrat-Capdevila et al. 2011). The conceptual group modeling process builds upon the results of Stage Three: stakeholders have gained experience in the application of conceptual modeling (i.e., CLDs) and the preliminary comprehensive model (i.e., the 'merged model') provides an indication of the scope of the issue, potential conflicts, alternative problem perspectives and solution strategies. The actual (conceptual) group modeling process can begin rapidly, as stakeholders are already acquainted with the method through the construction of individual CLDs. The merged model and the results of the questionnaires can function as an entry point for discussion. The group has to decide whether to use or revise the merged model that was built in the previous stages, or whether to start from scratch (i.e., a new model is jointly developed by the group from the beginning) (Vennix, 1996).

Quantitative participatory modeling can further build upon the conceptual modeling efforts proposed in the PMB framework and provide insights into complex system dynamics and potential solution strategies. Quantitative modeling involves the specifications of equations and model parametrization based upon available data and information. Various quantitative modeling methods exist that allow for stakeholder involvement, each having different application contexts and requirements, such as expertise of stakeholders and the facilitators, time requirements and the nature of the problem (e.g., lack of knowledge or conflicting interests). The most frequently used participatory modeling methods are system dynamics and agent-based modeling, fuzzy cognitive mapping and Bayesian networks (Voinov and Bousquet, 2010). Quantitative *system dynamics* modeling requires the conversion of the group-built CLD into a stock-and-flow diagram, to which parameters and equations are subsequently added (Vennix, 1996; Sterman, 2000; van den Belt, 2004). For an *agent-based modeling* approach, the individual and group-built CLDs can be interpreted as individual and collective mental models and thus can support the design of agents (Etienne et al., 2011; Scholz, 2016). *Fuzzy cognitive mapping* allows for assessing the plausibility of cognitive maps and generating scenarios (e.g., van Vliet et al., 2010; Jetter and Kok, 2014). Causal loop diagrams can also be used in the design of qualitative and quantitative *Bayesian networks* (van Kouwen et al., 2008; Giordano et al., 2013).

The modeling process usually proceeds in an iterative manner. For example, findings from quantitative analyses can necessitate a revision of the group-built CLD. In all model stages, the outcomes and proceedings of the model building need to be documented in a transparent way in order to inform non-participating stakeholders (for example through reports or action plans).

3.5. Stage Five: institutionalized participatory modeling

While project-oriented and short-term group model building research has yielded remarkable outcomes (see Rouwette et al., 2002), there has been little implementation of long-term participatory processes (Voinov and Bousquet, 2010), even though overcoming barriers towards stakeholder involvement and implementing adaptive management requires long-term engagement (e.g., Hatzilacou et al. 2007; Camacho et al., 2010; Allen and Gunderson, 2011) to adapt the strategies, values and institutions to current challenges and achieve social learning (Pahl-Wostl et al., 2007).

Social learning requires informal discourse in which water management problems are discussed, and the stakeholder group strives to develop the capacity to solve problems collectively (Pahl-Wostl et al., 2007). This does not imply consensus but at least the ability to deal constructively with controversial perspectives. These informal learning processes need to be linked to formal policy making in order to effectively facilitate new routines or practices (Sendzimir et al., 2010). Such linkages might be a formal mandate for participatory processes, legal obligations that result from participatory processes, representation of stakeholders in committees, or clearly defined governmental involvement in stakeholder processes. With respect to participatory model building, water agencies can function as a link between formal water management and informal learning processes. Water agencies (e.g., water boards or watershed organizations) are often located at the interface between policy development and implementation where close collaboration with stakeholder groups is particularly important. To function as such a link, water agencies require adequate funds, skills and mandates to ensure long-term financing and organization of collaborative management processes.

The MTF is applied as an analytical tool in the "institutionalized participatory modeling" stage of the proposed PMB framework (Stage Five). The analysis of institutionalization requirements includes financial instruments, dissemination of information and knowledge, as well as the roles of stakeholders in the learning process and rules for decision making. For example, a facilitator may be required for the group discussion and to elicit knowledge and insights from stakeholders. In addition, a process coach can examine the group-internal social processes and provide skills for mediation of conflicts (Richardson and Andersen, 1995). Importance can also be attributed to emergent leadership which may be essential for facilitating the implementation of solution strategies (e.g. Möllenkamp et al., 2008).

The ex-ante analysis is based upon previously gathered information about systemic barriers and drivers of institutionalization from the problem diagnosis in Stage 1, as well as individual interviews and group processes in Stages 3 and 4 (further expert interviews can be conducted as well). Specific process steps towards institutionalized participatory modeling are defined in the form of action situations that aims at overcoming an institutionalization barrier (e.g., lack of modeling skills) or support a driver (e.g., existing cooperation between stakeholders). Again each action situation is further specified by expected influencing factors, aspired outcomes (see Section 3.3) as well as stakeholders that need to be involved. A pathway towards institutionalized participatory modeling is developed by linking action situations through time. This pathway can provide orientation to stakeholders in their efforts to achieve transformative change and long-term continuation of the process by identifying suitable measures to develop skills and capacities. The pathway should be revised in case new barriers, drivers or implementation challenges (e.g., stakeholders who refuse to cooperate) are identified.

4. Application of the PMB framework in Québec

The research team explored the use of the PMB framework in the du Chêne watershed in Québec in cooperation with the local watershed organization (L'Organisme de bassins versants de la zone du Chêne: "OBV du Chêne"). The OBV du Chêne is located in Southern Québec, Canada, about 40 km south of Québec City, and manages one of the 40 priority integrated watershed management zones in the province. The OBV du Chêne was formed in 2007 through a joint effort of the Union of Agricultural Producers and the Municipalité Régionale de Comté (MRC) Lotbinière. The du Chêne is the major watershed in the Zone du Chêne and along with a number of smaller adjacent watersheds, directly discharges into the Saint Lawrence River. The du Chêne watershed covers 800 km^2 with intensive agricultural and forestry production which has resulted in pollution problems and soil erosion.

The participatory process started in 2010 with a meeting of McGill researchers and the OBV staff to consider the participatory modeling process as a potentially useful tool to improve relations between stakeholders in the du Chêne watershed, and to learn about different perspectives of the causes, consequences and solutions regarding the water quality problem in the watershed.

4.1. Problem framing and stakeholder analysis (Stage One)

The problem and stakeholder analysis was accomplished in close cooperation with the OBV du Chêne. At the beginning of the participatory modeling process, a thorough literature review and interviews with staff of the du Chêne watershed organization were conducted. The OBV du Chêne determined that the major issue in the watershed was declining water quality mainly due to eutrophication and chemical contamination. The sources of water pollution were thought to originate from the agriculture, forestry, and municipal sectors. However, the exact pathways and quantities were unclear, and further research was required to identify solution strategies. The research project adopted this initial problem frame from the OBV du Chêne, as it was broad enough to motivate many stakeholders to participate. In addition, this broad problem definition was expected to include different, more specific problem perspectives from other stakeholders.

Available information was included in a MTF database to analyze the complexity of the water quality issue and associated stakeholders in an integrated and systematic manner. The problem analysis started in 1960 to consider long-term impacts from the agricultural, municipal and forestry sectors. The level of detail of the problem analysis increased with time due to greater information and data (e.g., systematic monitoring of water quality data in the du Chêne watershed was not started until 2005). Important historical events for water quality management include the Programme d'assainissement des eaux du Québec (PAEQ) initiated in 1978 by the provincial government to foster water treatment in the municipal and industrial sectors as well as improved manure practices in agriculture (Gravel, 2006). The Règlement sur les exploitations agricoles (REA), implemented in 2002, includes important regulations regarding diffuse pollution from agriculture (including the development of fertilizer management plans, and the limitation of agricultural expansion in degraded watersheds).

Before the new Québec Water Policy in 2002, local and regional county municipalities were responsible for enforcing environmental law and managing rivers and adjacent areas. The Québec Water Policy introduced a participatory integrated watershed-based management approach. Beginning in 2002, watershed agencies were formed at local and regional levels to develop and implement a master plan for water to comply with priorities, guidelines, regulations and legislation at the national, provincial and municipal levels. Plans have to be submitted for evaluation and approval by the Minister of State for the Environment and Water. The watershed organizations are composed of representatives of stakeholder groups comprising citizens, elected officials of municipalities or regional county municipalities, and water-user representatives, such as the agricultural or industrial sectors. Provincial government representatives act as facilitators and provide scientific and technical support but do not have voting or decision rights (Baril et al., 2005). Watershed-based management is synchronized at the provincial levels through a general reference framework established by the Ministère du Développement durable, de l'Environnement et des Parcs (MDDEP, 2002). The Le Regroupement des organismes de bassins versants du Québec (ROBVQ) represents local watershed agencies (i.e., OBVs) and is another central actor that fosters integration of local water management in Québec. Thus, the OBVs are embedded in a multi-level water governance framework. Due to the central importance of the OBVs, the du Chêne watershed was chosen as an appropriate boundary for the participatory process.

The Board of Directors of the OBV du Chêne aims to represent all water-related stakeholders in the Zone du Chêne. Through the analysis of stakeholder roles, attributes and dynamics, it was determined that crucial participants were the staff of the OBV du Chêne and representatives from the agriculture, municipal, forestry, tourism, environmental and civil society sectors. The analysis of stakeholder dynamics highlighted the possibility of future participation by representatives of the industrial sectors. In particular, the shale gas industry was emerging as a new stakeholder in the watershed at that time, due to exploratory drilling activities. However, the development of the industry was stopped in 2013 through a moratorium by the provincial government that prohibits drilling, fracturing and injective testing in the area (OBV du Chêne, 2014a).

4.2. Process design (Stage Two)

During the preparatory meeting, the staff of the OBV du Chêne emphasized the importance of linking the participatory modeling process to the formal water management framework in Québec. A tangible outcome was expected from the participatory process to support the OBV du Chêne in fulfilling their formal obligations (e.g., develop a master plan for water, foster knowledge dissemination, and raise awareness). The outcomes from each step in the participatory modeling process and its linkage to the formal mandate of the OBV du Chêne were thus discussed in detail by the research team and the staff of the OBV.

Fig. 3 shows a simplified conceptualization of the modeling process (blue elements) and the formal water management process (white elements) in the du Chêne watershed. The OBV du Chêne was established in 2007 on the basis of the Québec Water Policy. By 2010, knowledge regarding water quality and other attributes of the watershed was gathered, and a technical committee was formed consisting of all major stakeholder groups (agriculture, economic, municipal and civic sectors). From 2010 to 2014, a participatory analysis of the basin was conducted by the staff of the OBV to produce a portrait (OBV du Chêne, 2014a) and a diagnostic report (OBV du Chêne, 2014b) of the watershed. Based on these findings, the watershed organization defined specific problems and objectives (OBV du Chêne, 2014c). This work resulted in a master plan for the watershed specifying concrete actions and responsibilities (OBV du Chêne, 2014d).

The participatory modeling process entered the official water management process at different points in time. The involvement of the researchers started in 2010 with a preparatory meeting in which a CLD was constructed with the OBV staff. The members of the OBV du Chêne learned about the method and decided to initiate an individual modeling process in October 2010. The low time and resource requirements of the individual modeling stage allowed water managers to commit to the process, since separate funds for the testing of new facilitation methods were not available. The outcomes of this process were intended to be a collection of individual CLDs developed by each stakeholder and a merged overall CLD of all perspectives (as described in Section 3.3). The individual modeling process was aimed at improving contacts and communication between the watershed organization and stakeholders to support the participatory analysis of the basin. Based on positive experiences with the individual modeling stage, the watershed organization decided to proceed towards the group model building stage to support group discussions in an upcoming stakeholder meeting (see Section 3.4). Thus, the development of a group model was planned to improve the understanding of problems in the watershed and allow staff and stakeholders of the OBV to gain new methodological knowledge. In a next step, the development of a quantitative system dynamics model was discussed with the staff of the OBV based upon the previously developed individual and group-built CLDs. A system dynamics model was considered helpful to test different solution strategies for the water quality problem (e.g., alternative farming methods, planting of riparian vegetation) under varying conditions (e.g., changing precipitation patterns due to climate change, population dynamics), which could inform the choice of objectives and the preparation and revision of the watershed master plan. As the pathways of nutrients and suspended solids are a central concern in the watershed, a model coupling approach was discussed that would dynamically couple a physically based model (i.e., the SWAT model) to the group-built system dynamics model in order to assess the effects of policies (e.g., on soil erosion) in detail (see Inam, 2016 and Inam et al., 2017a,b for more details on this model coupling approach).

The application of the MTF was considered to be useful for process design and evaluation. The analysis of the linkages of the modeling process demonstrated how the participatory process fed into the formal decision making process (see Fig. 3), and thereby helped to fulfill the formal mandate of the OBV. This assisted staff members in clearly communicating the purpose of the process to stakeholders and government agencies.

4.3. Individual modeling (Stage Three)

Individual models were built in eight stakeholder interviews. The stakeholders were visited by two facilitators (i.e., one staff member and one researcher) at their home or office to minimize efforts required by stakeholders, such as time requirements for traveling. The choice for interviewees represented the composition of the du Chêne Watershed Organization, and included two representatives of civil society (an environmental NGO and a citizen's group), three representatives from different municipalities and three representatives from the economic sector (tourism, agriculture and forestry). These stakeholders brought a broad range of expertise to the participatory process, including training in environmental management, biology, ecology, and economics. CLDs were built by each interviewee individually while methodological support was jointly provided by two staff members of the du Chêne Watershed Organization and one of the authors. The staff members received training through a two-hour preparatory meeting in which the systems thinking method was presented and an individual CLD built. The stakeholder interviews took approximately 1.5 h each and the entire individual interview process was accomplished in three days.

According to the guideline in Section 3.3 (i.e., *problem*, *causes*, *consequences*, *feedback*s, *solutions*, *barriers*), the construction of the individual stakeholder CLDs began with the definition of the problem variable. All participants agreed that water quality was the major *problem* in the du Chêne watershed. While emissions from agriculture and municipal sectors were seen as *causes* by all participants, the role of forestry was not seen uniformly by stakeholders (i.e., a number of models did not include impacts from forestry). The main suggested impacts from agriculture stemmed from soil erosion and the use of pesticides and fertilizers that entered the river through the agricultural drainage system. River dredging and drainage systems were also seen as having major impacts on water quality by some stakeholders as they increase the velocity of river flow and disturb natural filtration processes. The impact of the municipal sector was related to deficient

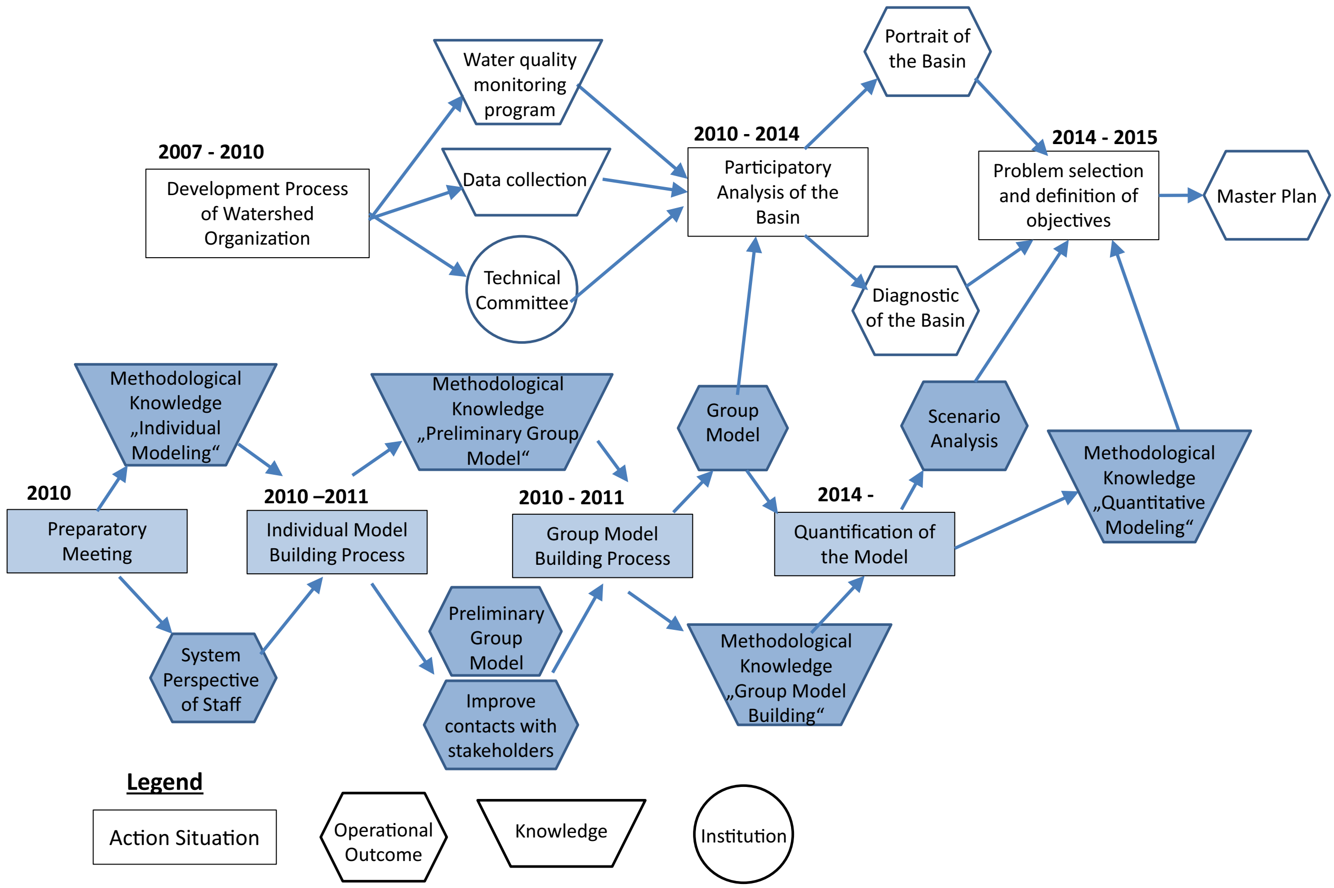

Fig. 3. Analysis of the linkages of the group model (blue) building process to the water management (white) process in the du Chêne watershed (using the MTF). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

wastewater infrastructure in urban areas and septic tanks at isolated residences. Emissions from the road network were also seen as a relevant source of emissions by some participants. Forestry contributed to the water quality issue through deforestation which caused higher water temperatures and soil erosion. Natural emissions (e.g., from wetlands) were mentioned as an important factor by some stakeholders.

Participants considered the *consequences* of the water quality issue on the environment (e.g., aquatic flora and fauna), tourism and recreation (e.g., swimming and fishing), and potable water supply (e.g., higher treatment costs). Several reinforcing *feedback loops* were identified (see Appendix B); for example, in the case of a declining standard of living in the du Chêne watershed, this would be expected to lower the willingness of citizens to protect the aquatic environment as socio-economic issues become a priority. As a consequence, water quality could deteriorate and the standard of living might be reduced even more. Balancing feedback loops to improve water quality included *solutions* proposed by stakeholders such as stricter legislation and implementation of regulations (e.g., REA), installment of riparian vegetation strips, reforestation, investment in wastewater infrastructure and education campaigns. For example, a farmer proposed more hands-on measures such as "placing stones in the riverbed" to reduce erosion while representatives from the municipalities included more policy oriented approaches such as "application of the Environmental Quality Act". Responsibilities for the implementation of these measures were seen on a broad societal scale, including provincial ministries, municipal administration, OBVs, agriculture clubs, foresters and civic society. *Barriers* were related to the costs of solution strategies and a lack of environmental consciousness by several stakeholder groups.

The outcomes of these individual model building sessions consisted of a number of multi-faceted CLDs. The participants were generally satisfied with their models and believed that they reflected their point of view in a comprehensive way. Fig. 4 presents a translated CLD model (upper part of Fig. 4) developed by a stakeholder during a 1.5-h interview, and which was later digitized by the facilitators using the Vensim software (lower part of Fig. 4).

The model in Fig. 4 shows the perceived causes and consequences of the water quality problem in the du Chêne watershed as well as preferred solution strategies and implementation barriers from the perspective of a single stakeholder. Apart from the "Treatment Loop", all feedback loops include the variable "Education and sensibilization" (see Appendix A for a detailed description of all loops). There are various balancing feedback processes that include solution strategies that are expected to balance the water quality problem (e.g., new cultural practices, implementation of environmental regulations, or natural conservation). Two implementation barriers point to limited resources and opposition of stakeholders from the agricultural sector. In Fig. 4, only one reinforcing feedback loop is included which refers to loads of organic environments, such as wetlands, that contribute to natural emissions of organic materials. In summary, the CLD depicts the stakeholder's mental model of the water quality issue including environmental (e.g., wetlands, forest cover), economic (e.g., financial resources), technical (e.g., sewage treatment, septic tanks), and social (e.g., education, sensitization) aspects.

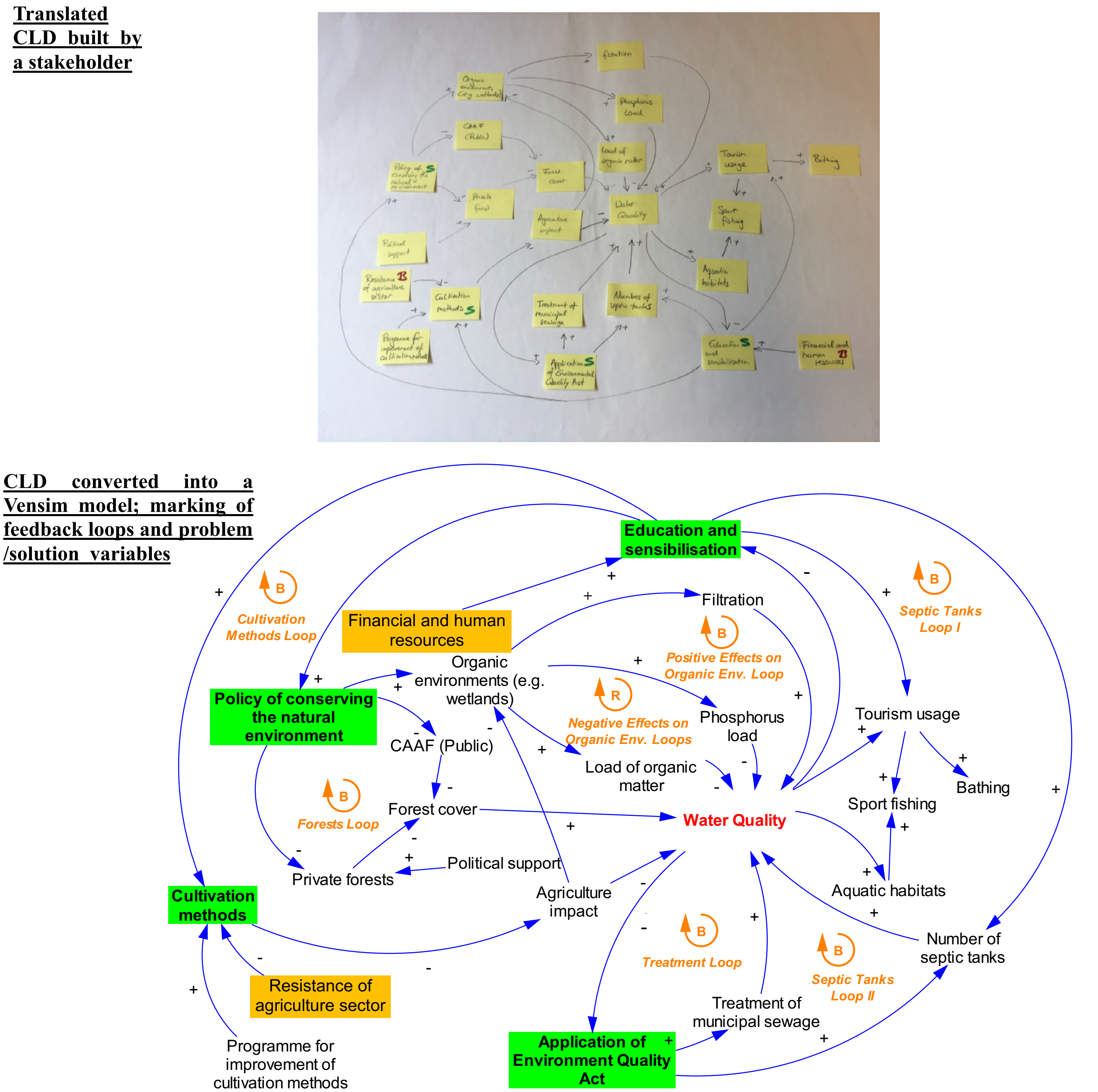

Fig. 4. Example of a CLD from a 1.5-h interview (translated model above; digitized and analyzed model below). The red variable represents the problem variable. Green variables are proposed solutions; orange variables are perceived implementation barriers. A '+' sign denotes a parallel behavior between linked variables, while a '–' sign indicates an inverse behavior. Balancing ('B') and reinforcing ('R') feedback loops are marked with orange symbols (see Section 2.2 for more details). CAAF stands for "Contrat d'Aménagement et d'Approvisionnement Forestier" (supply and management agreement for forests). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Subsequent to the individual interviews, a merged model from all stakeholder-built CLDs and a related workbook were prepared by one of the authors (see Appendix A). In the workbook, the merged model was presented successively by using thematic models, each highlighting a specific thematic aspect of the overall model: erosion and deforestation problems; water pollution and economic impacts; impacts of water quality on tourism and quality of life. These models are not independent from each other and it was underlined that the three models are intertwined and only presented in this way for clarity. The staff members of the OBV du Chêne decided to directly enter the "involvement phase" (Stages Four and Five) of the PMB without sending the workbook out to stakeholders. Nevertheless, the workbook demonstrated the ability of the method to provide an integrated picture of the water quality issues in the watershed.

4.4. Group model building (Stage Four)

Based upon the positive experiences and the methodological knowledge that was acquired, a group modeling exercise was integrated into a regular meeting of the OBV du Chêne. The group exercise was attended by ten stakeholders who represented all sectors involved in the water quality issue. Two researchers supported the staff members to structure the group exercise. Instead of discussing the general problem of "water quality", the group decided to concentrate on the more focused problem of soil erosion as they perceived it to be the major reason for water quality problems in the du Chêne watershed.

The discussion of causes and consequences of soil erosion confirmed the diversity in stakeholder perceptions that had been revealed through the individual modeling process. The group exercise took approximately 1.5 h and helped to clarify differing definitions of terms and levels of abstraction with respect to causes and consequences. Each model variable was discussed by the group, and only added to the model if all participants agreed upon its meaning and validity. This approach resulted in a structured and in-depth discussion. The model building process was considerably slower than the individual model building given all the discussion. However, this provided the stakeholders with a unique opportunity to discuss points of contention in a productive way, learn about the perspectives of others, and discover the interconnected system structure of soil erosion and its link to water quality. As considerable time was needed to clarify stakeholder contributions to the discussion, the resulting model (Fig. 5) contains a lower number of variables and connections than the individual models (cf. Fig. 4). The process of detailed explanation and rephrasing of statements is an important step towards social learning.

The OBV Du Chêne was satisfied with the group process, as the modeling exercise was the first time that stakeholders had discussed water issues in the du Chêne watershed in an active manner. Despite previous repeated attempts of staff members to stimulate an open discussion, stakeholder meetings had merely been one-way 'information' meetings. The structured modeling process helped the stakeholders to discuss the causes and consequences of poor water quality including socio-economic, technical and environmental aspects.

Original CLD built by the stakeholder group in the Québec case study

Digitized and translated group model

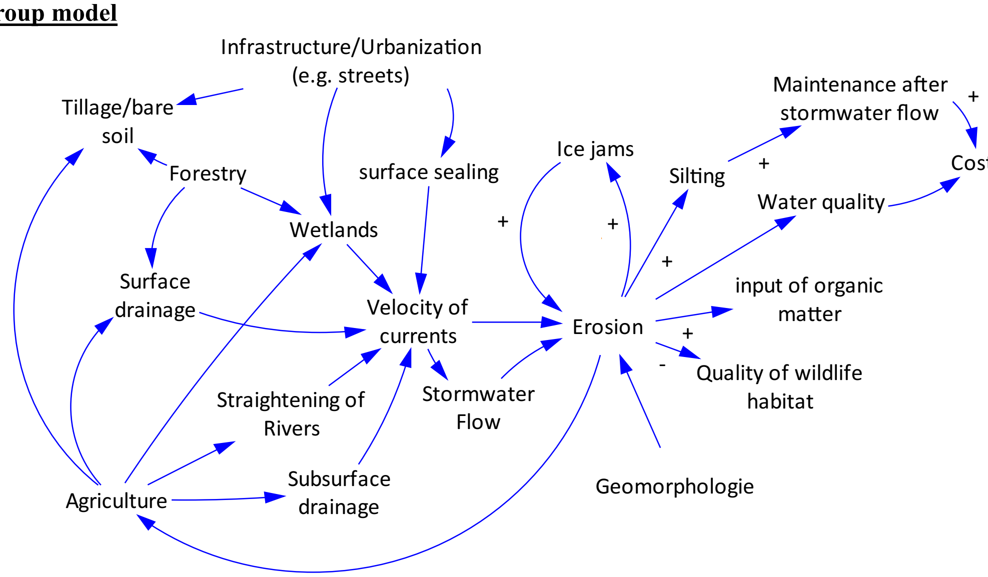

Fig. 5. Group model of soil erosion management in the du Chêne watershed in Québec (original model, above, and digitized model below). The digitized model does not contain separate variables that were not connected to the model: "riparian vegetation strips"; "soil conservation practices"; "profit".

The modeling process was evaluated through a questionnaire that was handed out to all participants. All respondents agreed that the group model building method supported discussion and development of a deeper understanding of the water quality issue in the du Chêne watershed. The majority of participants suggested that the group modeling process continue in the future in order to explore the soil erosion problem and other issues related to soil erosion and water quality in more depth. In addition, some respondents explicitly asked that the PMB process move towards quantification of the model and subsequent scenario analysis. Criticism was mainly related to the differing involvement of participants (i.e., some participants chose to contribute more to the discussion than others). A continuation of the participatory modeling process could address these demands by offering more time for discussion and additional opportunities for participants to express their points of view.

Following the group model building process, the development of a quantitative system dynamics model based upon the qualitative models from the individual and group model building process was planned in a follow-up meeting of McGill researchers and OBV staff. Due to the prioritization of the soil erosion problem, the model was intended to initially focus on the simulation of erosion pathways and the effectiveness of measures, such as the improvement of riparian vegetation strips. The simulation model was expected to help the OBV in selecting management actions to improve water quality in the du Chêne watershed. Therefore, a model coupling approach was designed to dynamically couple the system dynamics model (addressing socio-economic aspects of the water quality issue) to a SWAT model (simulating physical and environmental processes) (cf. Inam, 2016, Inam et al., 2017a, b). However, missing streamflow data for the du Chêne created a barrier to quantitative modeling. The installation of streamflow gauging stations in the watershed is an example of a long-term measure, which requires substantial investment. Such broader requirements for systemic change towards participatory and sustainable water management (further examples are the development of facilitation skills or the implementation of new legal frameworks and funding structures) are prevalent in water resources management practice. This motivated the development of Stage Five of the PMB framework, which allows for the systematic analysis of long-term solution strategies and opportunities for institutionalized participatory modeling.

4.5. Institutionalized participatory modeling (Stage Five)

Up to this point, the participatory modeling process was jointly facilitated by the research group and staff members from the OBV du Chêne. Throughout the process, the staff members were included as much as possible in the application of the participatory methods to develop their capacity to independently continue the process. Legislative conditions for the initiation of the participatory modeling process are supportive given that the OBVs have flexibility in their choice of approaches for stakeholder participation. However, several challenges for the long-term continuation and institutionalization of the modeling process were revealed during the participatory process, including the availability of modeling skills, financial resources, decision-making power, broader experiences in participatory modeling, and a coherent water governance framework. Fig. 6 shows a simplified pathway to overcome the

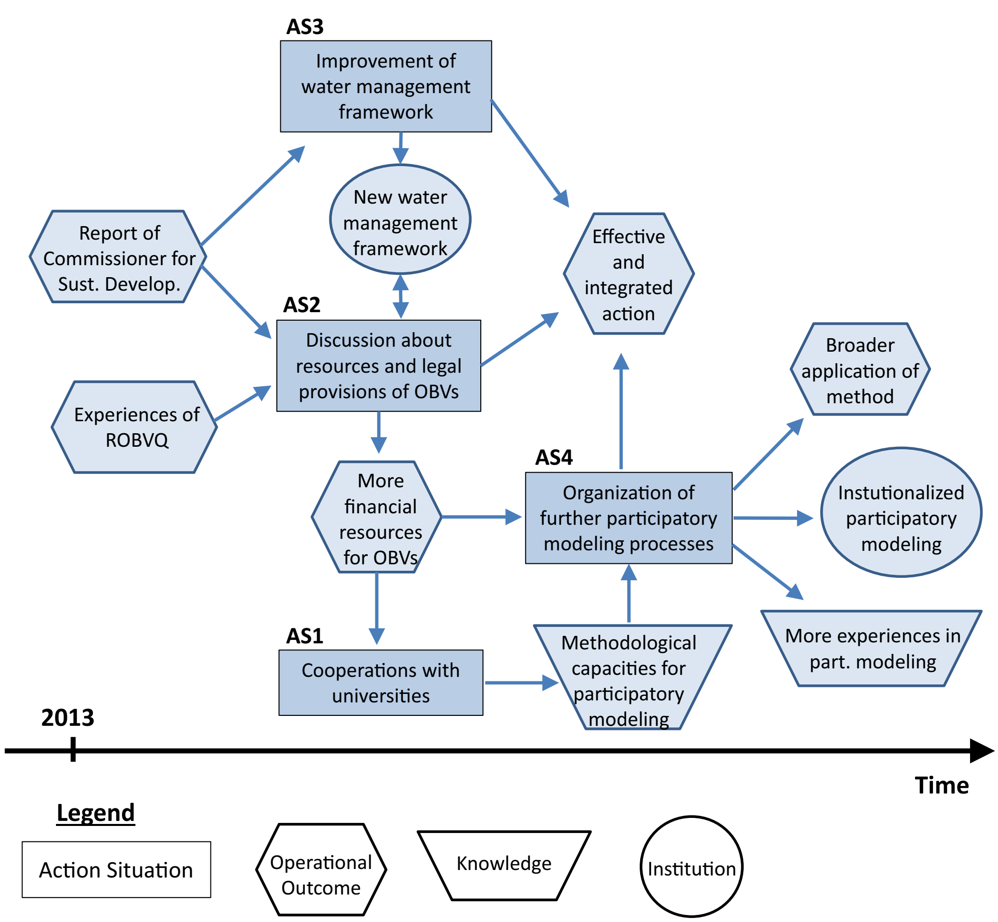

Fig. 6. Potential pathway towards institutionalized participatory model building in the du Chêne watershed. The pathway includes required action situations (AS) and related inputs and outputs. Further information about the pathways (e.g., stakeholders participating in action situations) can be included in the MTF database.

detected barriers of long-term participatory modeling processes in the du Chêne watershed. This is explained in more detail below.

First, while qualitative system analysis with the help of CLDs turned out to be quite intuitive, the development of a quantitative system dynamics model requires significant modeling skills. OBV staff would need further training in modeling to autonomously continue the process in the future. Long-term cooperation between universities (AS1) in the region and OBVs is a promising approach to ensure methodological support and modeling skill development.

Second, the long-term involvement of scientists in the process as well as the establishment of a streamflow gauging network in the du Chêne requires financial resources and decision-making power (AS2). Until now, the OBVs have not had sufficient funding for a strategic partnership with universities, but mainly depended upon resources from stakeholders (e.g., municipalities). This lack of funding and dependence upon the goodwill of stakeholders influences the OBV's ability to implement measures and strategies laid down in their master plans (ROBVQ, 2013; CCD, 2013; Medema et al., 2015).

Third, there is further potential for improvement of water management in Québec (AS3). For instance, an action plan for water has been requested by the Sustainable Development Commissioner (from the Ministère du Développement durable, de l'Environnement et des Parcs) and the ROBVQ that involves all governmental agencies and supplements water master plans in the watershed (ROBVQ, 2013; CCD 2013). Another request by the Sustainable Development Commissioner and the ROBVQ relates to a management framework that specifies responsibilities between different entities of the water system, including OBVs, ministers, and municipalities (CCD, 2013). Such a framework would support vertical integration (i.e., across management levels) as well as horizontal integration (i.e., across sectors such as water management and land planning) within the water governance system in Québec.

Finally, the initiation of further participatory modeling processes in Québec is needed (AS4) for experience to be acquired and the potential of participatory model building to be demonstrated to a wider audience (i.e., other OBVs, the ROBVQ and provincial ministries). As participatory modeling is increasingly applied in research and teaching at universities in Québec (e.g., at McGill University, see Halbe et al., 2015b), more students, scientists and practitioners have the required methodological expertise that is necessary for a broader application of participatory modeling approaches.

5. Discussion

The case study in Québec demonstrates the usefulness of the PMB framework for initiating participatory modeling processes in unfavorable contexts (i.e., limited time, financial resources and methodological knowledge). While the time requirements for the researcher were considerable (about 3–4 months for problem and stakeholder analysis and individual modeling), the time requirements for other stakeholders, such as the du Chêne watershed organization (about 3–4 weeks of involvement) and interviewees (about 1–1.5 h each), were lower. The extensive involvement of a researcher was needed to test, evaluate and refine the new PMB framework. In the future, we anticipate that Stages One to Three of the PMB framework can be accomplished with less involvement of researchers through the preparation of a website that contains guidance documents and further case study examples. The results of the exploratory phase in the case study comprise a systematic analysis of stakeholder perspectives on the water quality issue and the development of a holistic system understanding, which were explicitly mentioned in an official report of the watershed organization (OBV du Chêne, 2014b). The study revealed that further research and action is needed on economic and institutional aspects of the problem (e.g., effective policies to foster reforestation), as well as streamflow monitoring in the watershed to allow for more detailed analyses of emission pathways. Besides these more problem-related outcomes, the modeling process significantly improved the discussion process and relationships between stakeholders.

Without the exploratory stakeholder participation phase of the PMB framework (Stages One to Three), it is likely that participatory modeling would not have been applied in the case study due to minimal funding, time and expertise. Stakeholders were not aware of participatory modeling even though participatory water management was desired. The PMB framework is thus a promising approach to support the widespread initiation and application of the participatory modeling method in water management practice. Watershed agencies can test the appropriateness of participatory modeling step-by-step during the exploratory phase of the PMB framework, and decide from the insights gained whether more intensive involvement is appropriate in the specific case study. The PMB framework needs to be used in an iterative way to deal with the complexity of water resources issues. For example, findings from individual interviews (Stage Three) can require a revision of the initial problem and stakeholder analysis (Stage One) and process design (Stage Two).

The use of the MTF for process design (Stage Three) allows for a systematic analysis of the participatory process and its context. Such a systematic process design supports process monitoring and assessment, and based upon this, an iterative adaptation of the process design to challenges and opportunities (such as a change in stakeholder composition or funding options). More systemic case-specific challenges of stakeholder participation and requirements of institutionalized participatory modeling are addressed in Stage Five of the PMB framework. Of course, the use of the MTF alone does not dissolve barriers to institutionalized participatory modeling, such as inadequate funds or limited capacities. However, analyzing requirements for institutionalizing participatory modeling allows for a more strategic stakeholder selection (Stage One) and process design (Stage Two), for instance by including stakeholders who can support capacity building or even act as process facilitators in the long term. In addition, the MTF can be used to systematically compare and to facilitate the exchange of experiences between cases (Knieper et al., 2010; Pahl-Wostl et al., 2012), for example regarding barriers and drivers of participatory processes (e.g., Sendzimir et al., 2010; Schlüter et al., 2010), and to help envision a more supportive institutional structure for participation (e.g., Halbe et al., 2013). In this way, challenges that were faced during the participatory modeling process can point to the need for broader changes in water governance systems. Further research is needed to gather more case-specific data on barriers and drivers of participatory modeling processes, as well as systematically reviewing and synthesizing such context-specific factors into general findings.

6. Conclusions

The proposed Participatory Model Building (PMB) framework addresses the challenges of initiating, designing and institutionalizing participatory model building processes in water resources management. To date, participatory modeling has resulted in promising outcomes under favorable contexts (e.g., available funds) such as research projects, but widespread implementation is limited given the "unfavorable contexts" which often exist in practice (e.g., insufficient time, financial resources and facilitation skills).

The PMB framework provides a stepwise approach for water managers to move towards stakeholder involvement and integrated water resources planning and management. Starting with approaches that require little investment of finances and time as well as low levels of mediation skills (Stages One to Three), water managers and agencies can obtain insights on the need and applicability of a participatory approach. In the event of positive experiences, the process can proceed to the involvement stage (Stages Four and Five), where stakeholders meet and discuss the causes and consequences of a water resources problem, as well as policies and strategies for its solution. The PMB framework highlights the importance of capacity building in the water sector to allow for independent implementation of participatory model building processes (which is an important requirement for institutionalized participation). Case specific requirements for continuous and effective collaborative management processes can be analyzed using the Management and Transition Framework (MTF), an analytical tool that allows for the integrated analysis and planning of water management processes.

The proposed PMB framework was tested in multiple case studies in Canada (Québec and Ontario), Cyprus, Pakistan and Guatemala. The results from the case study in Québec were presented in detail in this paper and highlight the heterogeneity of stakeholder perspectives, which in turn underlines the need for participatory and interdisciplinary approaches in water management.

Acknowledgements

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Appendix A. Detailed description of feedback loops in Fig. 4

Balancing Loops (*uneven number of negative links*):

- **Treatment Loop:** Water Quality $\xrightarrow{-}$ Application of Environmental Quality Act $\xrightarrow{+}$ Treatment of municipal sewage $\xrightarrow{+}$ Water Quality
- **Septic Tanks Loop I:** Water Quality $\xrightarrow{-}$ Education and sensibilisation $\xrightarrow{+}$ Number of septic tanks $\xrightarrow{+}$ Water Quality
- **Septic Tanks Loop II:** Water Quality $\xrightarrow{-}$ Application of Environmental Quality Act $\xrightarrow{+}$ Treatment of municipal sewage $\xrightarrow{+}$ septic tanks $\xrightarrow{+}$ Water Quality
- **Cultivation Methods Loop:** Water Quality $\xrightarrow{-}$ Education and sensibilisation $\xrightarrow{+}$ Cultivation Methods $\xrightarrow{-}$ Agriculture Impact $\xrightarrow{-}$ Water Quality
- **Forests Loop:** Water Quality $\xrightarrow{-}$ Education and sensibilisation $\xrightarrow{+}$ Policy of conserving the natural environment $\xrightarrow{-}$ CAAF/Private Forests $\xrightarrow{-}$ Forest Cover $\xrightarrow{+}$ Water Quality
- **Positive Effects of Organic Environment Loop:** Water Quality $\xrightarrow{-}$ Education and sensibilisation $\xrightarrow{+}$ Policy of conserving the natural environment $\xrightarrow{+}$ Organic environments (e.g. wetlands) $\xrightarrow{+}$ Filtration $\xrightarrow{+}$ Water Quality

Reinforcing Loop (*even number of negative links*):

- **Negative Effects of Organic Environment Loop:** Water Quality $\xrightarrow{-}$ Education and sensibilisation $\xrightarrow{+}$ Policy of conserving the natural environment $\xrightarrow{+}$ Organic environments (e.g. wetlands) $\xrightarrow{+}$ Phosphorus Load/Load of organic matter $\xrightarrow{-}$ Water Quality

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jhydrol.2017.09.024.

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