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System Dynamics and Bayesian Network Models for Vulnerability and Adaptation Assessment of a Coastal Water Supply and Demand System

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Abstract: A coastal water supply and demand system is a highly uncertain and dynamically complex system. The degree of high uncertainty can arise from future climate change, population growth, water consumption trends, land use changes and socio-economic development, resulting in limited availability of empirical data. The effects of temporal and spatial interactions among such driving factors further contribute to the high dynamic complexity of coastal freshwater management. To effectively manage a coastal freshwater system with high levels of uncertainty and complexity, a participatory integrated System dynamics (SD) and Bayesian networks (BNs) modelling framework was suggested to assess the vulnerability and adaptation potential of a coastal water supply and demand system in a developing country. This integrated framework enhances our ability to understand the feedback-based dynamic processes of a dynamically complex system by developing systems maps and running the SD model. It also enables decision-makers to understand and address uncertainties through scenario development and participatory involvement in constructing and analysing the sensitivity of BN models. One of the most important aspects of the integrated modelling framework is the opportunity to increase the performance of the BN model by incorporating results from the SD model to populate conditional probability tables (CPTs) for some variables in the BN model. Subsequently, the best adaptation options identified from the BN model can be tested in the SD model over time. Finally, the framework enables water managers to identify appropriate management options, which incorporate multidisciplinary perspectives. Da Do Basin in Hai Phong City, Vietnam is used a case study to apply the participatory integrated modelling framework. Although, several steps (historical data collection, the development of a causal loop diagram, the initial SD and BN models) in the integrated modelling framework have been conducted in the case study, some future work is required to finalise the framework.

Keywords: Coastal freshwater system, Integrated modelling framework, Population growth, Sea level rise, Salinity intrusion

I. INTRODUCTION

Water resources management is confronted with many challenges. Population growth, urbanization, and economic development, in addition to the existing degree of exploitation, are widely considered to be the main factors contributing to a growing gap between water supply and demand, and ensuing water crises all over the world (Vörösmarty et al., 2010; Miller & Belton, 2014). This issue is especially prevalent in coastal areas of developing countries, where high rates of population growth and urbanization are likely to result in severe water scarcity (Vörösmarty et al., 2010). All of these issues are being exacerbated by climate change and associated sea level rise and changes to precipitation that are altering patterns of river discharge, and saltwater intrusion in estuaries (Dao & Suetsugi, 2014; Nguyen et al., 2008).

A coastal water supply and demand system involves complex natural and anthropogenic processes that are interactions between interdependent components with many feedbacks. Water availability is temporally influenced by climate variability and climate change. For example, the changes in sea level and river flows over time possibly lead to the temporal salinity intrusion (Nguyen et al., 2008), and thus temporally influence the variability of water availability. Similarly, population growth and land use change also dynamically affect water demand over time. As a whole, the vulnerability of coastal freshwater systems over time is affected by temporal changes in the states and levels of the main drivers. In addition, dynamically simulating the water supply and demand system is likely to provide greater understanding of system vulnerability to climatic and non-climatic changes. A holistic understanding of the temporal interactions of interdependent elements in the systems is likely to lead to more effective learning and management in complex systems (Winz et al., 2009), as well as consensus building for identifying robust adaptation options which could deal with both current and future conditions (Fussel, 2007).

Uncertainties also are an inherent part of coastal water supply and demand systems. Future climate change, river flows and sea level are uncertainties on the water supply side. Future population growth, land use change and water consumption trends are uncertainties on the water demand side.

Taken together, to effectively manage a dynamic coastal water supply and demand system where a high degree of uncertainty is present, there is a need to apply a participatory integrated approach that assists decision-makers to understand and deal with the dynamic and uncertain characteristics of the system, and so that they can initiate better management strategies.

II. AN INTEGRATED SYSTEM DYNAMICS AND BAYESIAN NETWORK APPROACH

2.1. The strengths and weaknesses of System dynamics and Bayesian networks

A system dynamics (SD) approach has been shown to be an ideal strategic water supply and demand modelling tool since it provides an understanding of the dynamic and complex nature of water supply and demand management to assist with forecasts, infrastructure planning, demand planning, and balancing supply and demand (Winz et al., 2009; Kelly et al., 2013; Sahin et al., 2016). SD software also enables modellers to use the result of hydrologic studies, and then model the relationships between the hydrology and other aspects of the system such as socio-economic development (Beall et al., 2011). Numerous scenarios can be also incorporated into one comprehensive model and analysed via an adjustable dashboard display (Sahin et al., 2016) to help decision makers understand the complex system and initiate better management strategies. However, SD applications have inherent limitations in dealing with uncertainties in water resource systems, especially under the forcing drivers of climate change impacts (Winz et al., 2009). This weakness of SD is well handled by Bayesian networks (Aguilera et al., 2011; Catenacci & Giupponi, 2013; Molina et al., 2013).

Bayesian networks (BNs) have proven to be powerful tools for assessing and predicting consequences of adaptation options under uncertain drivers such as climate variability and climate change (Aguilera et al., 2012; Catenacci & Giupponi, 2013; Molina et al., 2013; Richards et al., 2016). They can act as a decision-making support tool through consideration and analysis of different potential adaptation options accounting for system behaviour under uncertain future development (Farmani et al., 2012). BNs have this capacity because they can provide a flexible framework for interdisciplinary integration, in which climatic, physical, ecological and socio-economic phenomena can be incorporated to examine in a single framework (Bromley et al., 2005).

BNs are also used to simulate systems containing some degree of uncertainty caused by imperfect understanding or incomplete knowledge of the system's states (Bromley et al., 2005). This is due to their ability to incorporate different data sources from physical models' outcomes, field data, literature values and expert knowledge into a single framework for initiating management strategies (Barton et al., 2008; Catenacci & Giupponi 2013; Molina et al., 2013). Therefore, uncertainty can be handled more appropriately than in other modelling approaches.

However, it is widely recognized that BNs are not able to explicitly represent dynamic relationships and interactions among interdependent components in water systems (Borsuk et al., 2004; Cain et al., 2003; Marcot et al., 2006). In addition, practical implementation of BNs often requires discretization of continuous variables. This discretization may affect the relationships among variables and may produce misleading results (Kelly et al., 2013). In contrast, this is strength of SD modelling approaches, which are explicitly designed to represent inter-related temporal processes (Sušnik et al., 2012; Winz et al., 2009).

Ideally, the weaknesses associated with each of these two approaches could be overcome by combining them in an integrated modelling framework to model the complexity and uncertainty inherent in coastal freshwater systems, and achieve a more holistic and representative modelling outcome. More specifically, this integrated modelling approach (i) could complement the strengths and weaknesses of each modelling approach, and should be able to identify synergistic opportunities to improve the management of water supply and demand system; (ii) enhances our ability to understand the feedback-based dynamic processes of the complex system; (iii) enables decision-makers to understand and treat uncertainties through scenario development and participatory involvement; (iv) helps to initiate appropriate adaptation options from multidisciplinary perspective for water system decision-making.

2.2. An Integrated System Dynamics and Bayesian Network Framework

To address the challenge of linking complementary modelling approaches with complementary strengths and weaknesses, a participatory integrated SD and BN modelling framework was suggested to dynamically assess vulnerability and adaptation options of a coastal water supply and demand system to climatic and non-climatic drivers in a developing country. Ten steps of the integrated framework were proposed, based on the dynamic and uncertain characteristics of the coastal water supply and demand system, and strengths and capabilities of SD and BNs, as follows (Figure 1):

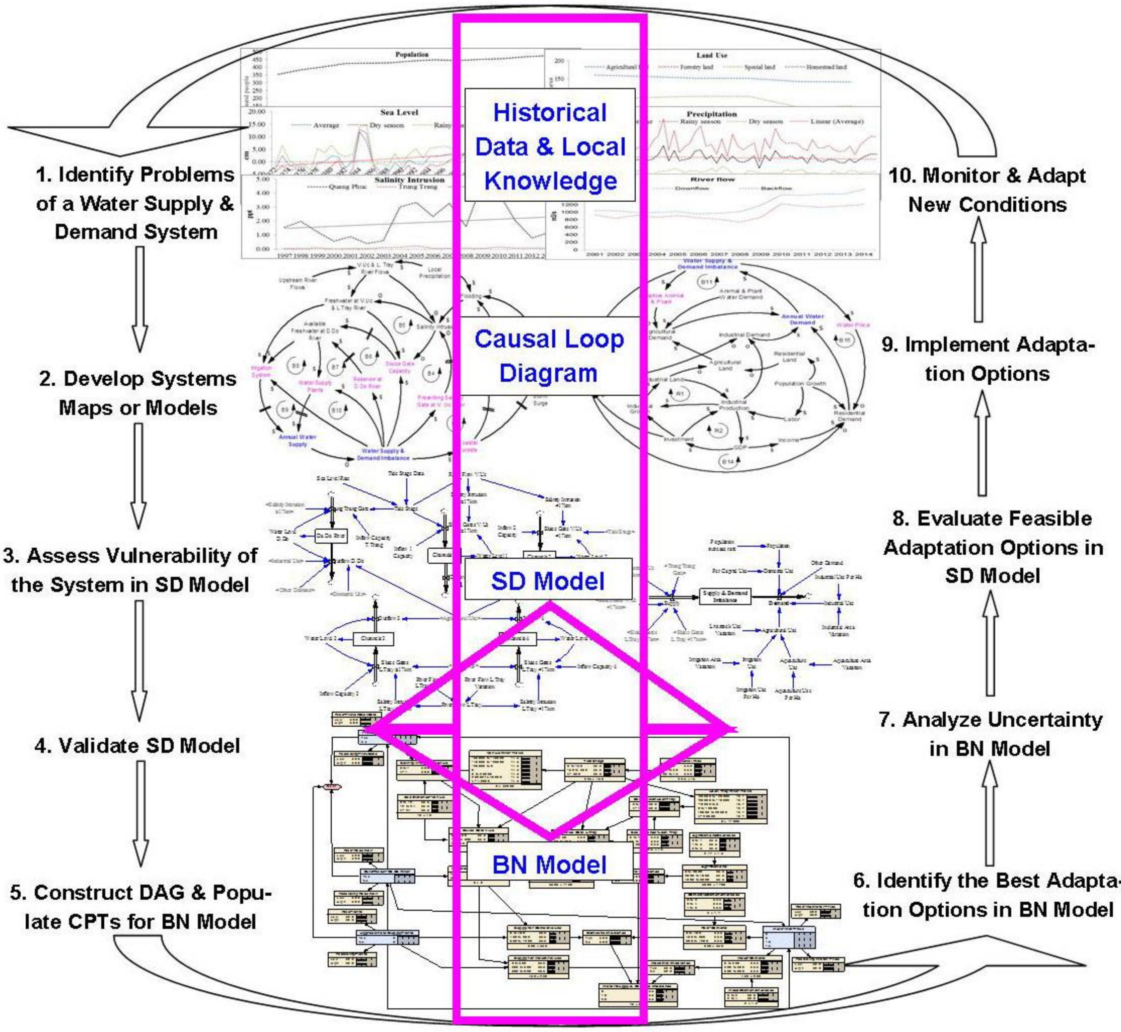

Figure 1: Architecture of a participatory integrated SD and BN modelling framework

(i) Identify problems by understanding the effects of historical climatic and non-climatic changes on a water supply and demand system,

(ii) Develop systems maps or models to understand the relationships among interdependent components in the system,

(iii) Incorporate a range of scenarios of climatic and non-climatic drivers into a SD model to identify system vulnerabilities,

(iv) Calibrate and validate the SD model by using historical and field data,

(v) Use information from the SD model, and historical data to construct Directed Acyclic Graphs (DAGs) and populate conditional probability tables (CPTs) with a participatory process,

(vi) Identify appropriate adaptation actions using the BN model,

(vii) Analyse uncertainties by conducting sensitivity analysis within/as part of a participatory process,

(viii) Evaluate the feasibility of adaptation actions derived from the BN model using the SD model,

(ix) Implement adaptation options,

(x) Monitor performance of the implemented adaptation options, and adapt with new conditions.

This integrated framework could be able to identify synergistic opportunities to improve the management of water supply and demand system. In addition, this framework enhances our ability to understand the feedback-based dynamic processes of a complex water system by developing systems maps and running the SD model. It also enables decision-makers to understand and address uncertainties through scenario development and participatory involvement in constructing and analysing the sensitivity of the BN model. One of the most important aspects of the proposed integrated modelling framework is the opportunity to increase the performance of the BN model by incorporating results from the SD model to populate CPTs for some variables in the BN model. Subsequently, the best adaptation options identified from the BN model can be tested in the SD model over time. This initiative enables water managers to validate and test the performance of models, and identify appropriate management options, which incorporate multidisciplinary perspectives.

III. A CASE STUDY

The participatory integrated SD and BN modelling framework will be applied to the Da Do Basin in Hai Phong City, Vietnam as a case study.

3.1. Local Contexts

Hai Phong is a coastal city in the Red River Delta in the north of Vietnam, and Da Do Basin is the largest area in the city (Figure 2). It provides freshwater for five districts in the city, including An Lao, Kien Thuy, Kien An, Duong Kinh and Do Son with a population of 550,000 people, and an average population density of 1,275 people/km^2 (HPSYB, 2014). Population growth with 1%/year, coupled with the high rates of industrialization and urbanization, are expected to lead to water shortages, possibly inhibiting socio-economic development for the coastal city (HPDNEM, 2013).

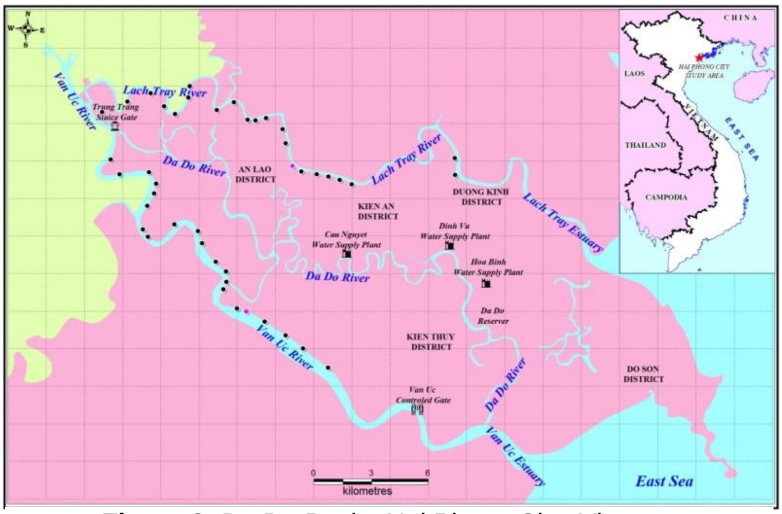

Figure 2: Da Do Basin, Hai Phong City, Vietnam

The topographic relief of estuaries in Hai Phong city is relatively low, above 1-1.5m of sea level, and thus gradual and tidal conditions occur. Seasonal hydrological patterns depend, therefore, on seasonal precipitation, river flows and sea level, tidal stage. The highest monthly sea level occurs between November and January, and the lowest level occurs between March and April. However, the highest monthly river flows happens between July and August, and the lowest between December and April. In addition, sea level rose about 20cm, and precipitation decreased slightly over 50 years, from 1965 to 2014. Consequently, water shortages are being exacerbated by sea level rise, and precipitation decrease, which are altering patterns of river flows and increasing saltwater intrusion in estuaries, especially during dry season, affecting freshwater availability (HPDNEM, 2013).

Obviously, the coastal freshwater supply and demand system for the Da Do Basin is affected by climatic and non-climatic drivers. Understanding these drivers and the influence of their seasonal interactions on freshwater availability in estuaries at different temporal scales is an urgent requirement. This knowledge will assist multiple-levels of stakeholders to identify and implement appropriate adaptation options to reduce the vulnerability of this coastal freshwater system to climatic and non-climatic changes.

3.2. Systems Maps

A Causal loop diagram (CLD) for a coastal water supply and demand (Figure 3) was developed, based on mental models generated at a workshop held in Hai Phong City, involving 35 people of water resource and climate change specialists from universities, research institutes and decision makers from Hai Phong City, local authorities, and water management practitioners in the Da Do Basin. In addition, the causal loop diagram was also generated based on historical data from Hai Phong, and the world literature review. The CLD provides a comprehensive conception of the drivers of imbalance in the coastal freshwater system, and the role and operation of potential adaptation options to reduce imbalance in the system.

Imbalance in this system is influenced by changing water supply and demand over time. Water supply is driven by sea level rise, river flows, precipitation and salinity intrusion. Precipitation and river flows are the main sources of water supply. However, these sources are decreasing over time due to a decline in precipitation in the region, leading to a decrease in river flows. In addition, water supply is further limited by salinity intrusion, which is driven by interactions between sea level rise and river flow decrease. Available water supply is also influenced by operation of the existing sluice gate system, and water extraction for the irrigation system and water supply plants for residential, agricultural and industrial use. The sluice gate system is intended to provide freshwater flows, and control salinity intrusion from the Van Uc River and the Lach Tray River to the Da Do River, and agricultural fields. This pathway provides freshwater for all activities in the Da Do Basin through the irrigation system and water supply plants (Figure 2). Water demand is driven by domestic use, agricultural use and industrial production over time. The local context shows that domestic uses and industrial uses of water are likely to increase over time because of population growth and increasing industrial production in the Da Do basin. This is depicted by two reinforcing loops (R1, R2), showing the relationships among population growth, industrial production and water demand. However, agricultural water use is likely to continue to decrease over time because agricultural land is being converted to industrial and residential land. Interactions and changes in domestic use, agricultural use and industrial production will drive increases or decreases in the water demand through time.

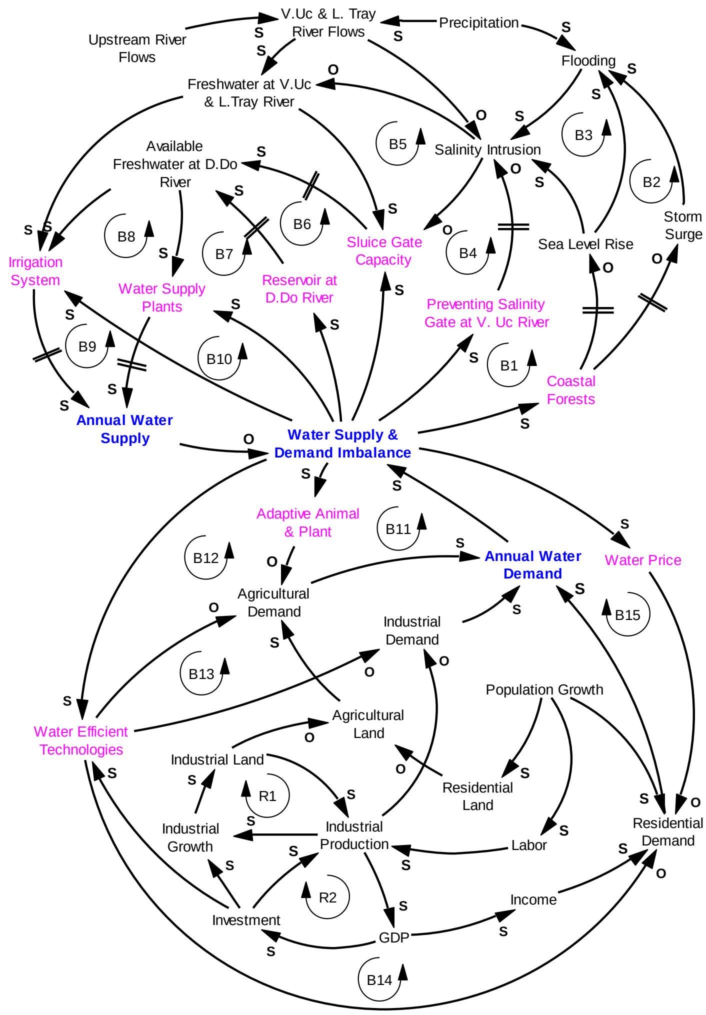

Figure 3: A CLD for a coastal water supply and demand
Legend: S (same direction), O (opposite direction), R (reinforcing), B (balancing), ≠ (delay), blue colour (main variables), black colour (influential variables), pink colour (adaptation options)

The change in water supply relative to water demand leads to an increase or decrease in the imbalance of the system through time. In this context, imbalance is defined as demand exceeding supply. The lower the available water supply, the greater is the system's imbalance for a given level of demand. Conversely, the higher water demand, the greater is the system's imbalance for a given level of supply. Once imbalance arises, it requires actions to secure freshwater for all activities in Da Do Basin by increasing freshwater availability or reducing water consumption or both as illustrated by 15 balancing loops (from B1 to B15), and two reinforcing loops (R1, R2).

Nine adaptation options were identified by the participants in the workshop. Six these adaptation options act to increase water supply, and three of these adaptation options act to decrease water demand. The first adaptation option to increase water supply is planting forests along the coast to restrict the effects of sea level rise and storm surge on freshwater in the Van Uc River and Lach Tray River by reducing saline intrusion into these rivers. These relationships act through three balancing loops (B1, B2 and B3). It is noticeable that sea level rise results in salinity intrusion further into upstream. As a consequence, the sluice gate system along these rivers will be closed; closing the sluice gates, limits provision of freshwater from the Van Uc and Lach Tray rivers to the Da Do River (B4), and agricultural fields. Therefore, building a salinity prevention gate at Van Uc River could be considered as a priority option. This aims to increase freshwater flow in the Van Uc River by preventing salinity intrusion into the river when a spring tide occurs, and retaining freshwater from the upstream or when appropriate, opening to drain the water into the sea. A salinity prevention gate will increase freshwater availability in the Van Uc River, and then increase water supply, as indicated by a balancing loop B5.

Increasing freshwater in the Da Do River by upgrading sluice gate capacity to increase water flows from the Van Uc River and Lach Tray River to the Da Do River, and building a Da Do River Reservoir are two other adaptation options which were identified by workshop participants. An increase in freshwater flow in the Da Do River will increase water supply, and thus reduce system imbalance, creating three balancing loops (B6, B7, and B8). In addition, upgrading water supply plants and irrigation system to increase water supply, and thus reduce imbalance are also depicted by two balancing loops (B9, B10). However, these two options will only succeed in increasing water supply if there is sufficient freshwater available at the Da Do River for inputs to the water supply plants and irrigation system.

In addition to the adaptation options to increase the ability to supply freshwater, workshop participants also identified adaptation options to reduce water demand. Applying adaptive plant and animal, water efficient technologies, and increasing water prices were identified as adaptation options to reduce water consumption by encouraging more efficient water use in households, agriculture and industry. By applying these adaptation options, annual water demand will potentially decrease, and thus reduce the imbalance in the system. These relationships are presented by five balancing loops (B11, B12, B13, B14, and B15).

Interactions between these 15 balancing feedback loops create a “Drifting goals” system archetype (Maani and Cavana, 2007). This archetype begins with standard goal seeking loops (B1 to B10), which attempt to increase water supply via some actions for relieving the imbalance. However, a difficulty often arises because of the delay associated with the time and effort required to increase water supply. Therefore, some time delay will exist between initial implementation of these adaptation options and subsequent increase in available water supply. The goal seeking loops (B11 to B15) are also capable of relieving the imbalance by decreasing water demand. However, the goal seeking loops (B11 to B15) are generally easier and take less time to implement than goal seeking loops (B1 to B10) (Maani and Cavana, 2007). This conception plays an important role in identifying and optimizing management interventions which will be effective for reducing imbalance in the coastal freshwater system.

3.3. System Dynamics and Bayesian Network Models

The SD model aims to assess the vulnerability of the coastal water supply and demand system over time. The coastal freshwater system is affected by both climatic and non-climatic drivers. Thus, it is necessary to examine simultaneously the effects of both types of drivers. Identifying the most influential factors of the system is an important step as modelling all components and their interactions in the system is not possible within the constraints of the current project. Essential variables for simulation were chosen based on a CLD and an analysis of the historical data related to coastal water supply and demand. In addition, variables were also identified by reviewing the world literature for more generic variables and the typical level of their effects on coastal water supply and demand systems. The most important variables, identified through these approaches, were incorporated into the SD model for assessing the system’s vulnerability.

The BN model aims to identify and prioritize the best adaptation options for maintaining the balance for the coastal water supply and demand in the Da Do Basin, Vietnam. The BN model was developed, based on the causal loop diagram and the SD model. This initial model will be revised by local experts in Hai Phong City. CPTs of some environmental variables will be learnt from the SD model and historical data, and other variables without available data will be populated by local experts through focus group discussions.

The outcome of the different adaptation actions will be estimated by observing the imbalance reduction at the output nodes, compared to a base scenario without the proposed interventions. Finally, the two adaptation options which deliver the greatest reduction in imbalance (%) with low cost, low risk and high feasibility will be then incorporated into the SD model to identify the most cost-effective adaptation options, which would result from implementing a particular adaptation option at a specific time in the future.

IV. CONCLUSIONS AND FUTURE WORK

This research aims to provide a participatory integrated SD and BN modelling approach for assessing the vulnerability and adaptation potential of a coastal water supply and demand system. This framework was initiated through analysing the strengths and weaknesses of SD and BNs, and in the light of the dynamics and uncertainties surrounding the coastal water supply and demand system. Da Do Basin in Hai Phong City, Vietnam is used as a case study to apply the framework.

Analysing historical data and building a CLD are one of the most important steps to understand the research problem. Historical patterns of sea level rise, precipitation, river flow, salinity intrusion as well as population growth and land use change in the case study were analysed to understand the influence of these drivers on the system. These patterns, coupled with participants' mental models obtained via a workshop, were used to build the CLD that provides a comprehensive conception of the drivers of imbalance in the coastal freshwater system. The CLD also clarifies role and operation of potential adaptation options to reduce imbalance in the system. Essential variables from the CLD were incorporated into the SD and the BN models to assess the vulnerability and adaptation for the coastal freshwater system over time.

Although, several steps in the integrated modelling framework have been conducted in the case study, some future work is required to finalize the framework. The SD model needs to be validated by historical data, field data and water management practitioners in the Da Do Basin before its vulnerability results will be used to populate CPTs for some variables the BN model. In addition, the BN model also needs to be revised, and CPTs without available date will be populated by experts in the city. Sensitivity analysis will be conducted before the two best adaptation options from the BN model are identified. These two best adaptation options will then be analysed in the SD model to identify the most cost-effective adaptation options, and assess their outcomes over time.

This framework should be able to identify synergistic opportunities to improve the management of a coastal freshwater system as it incorporates both SD and BN modelling approach to assess the vulnerability and adaptation options for a coastal water supply and demand system in a developing country. More specifically, it provides an understanding feedback-based dynamic process, and incorporates multi-disciplinary perspectives to effectively treat uncertainties in the complex and uncertain system.

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