Assessing Vulnerability and Adaptation for Coastal Water Supply and Demand Systems

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ABSTRACT

Water resources management faces many challenges in coastal areas of developing countries; where sea level rise and upstream flow decline coupled with high rates of population growth and urbanization have the potential to cause severe water scarcity. Understanding of the operational resilience of coastal freshwater systems is therefore needed to initiate appropriate strategies for the systems adapting climatic and non-climatic changes and their interactions. In this study, a system dynamics modeling approach was employed to explore the operational resilience of the coastal freshwater system in Da Do Basin, Vietnam to projected sea level rise, upstream flow decline and socio-economic development. Model results indicate that under current conditions, freshwater availability is sufficient to supply existing domestic, industrial and agricultural demands. However, the coastal freshwater system changes significantly and collapses under some plausible future scenarios. The model results helped decision-makers identify potential adaptation options which were then incorporated into the SD model to assess their effectiveness in reducing the vulnerability of the coastal freshwater system. The adaptation option of combining building pumping stations and increasing water price is considered as the most effective of the adaptation options, as it increased water volume in the storage system under future climatic and non-climatic changes.

Keywords: Population growth, decision support approach, scenario analysis, sea level rise, upstream flow decline, adapting coastal freshwater system

1. Introduction

Water supply and demand systems in coastal areas of developing countries are being threatened by both climatic and non-climatic forces (Al-Jeneid et al., 2008; Yang et al., 2015). Climate change will significantly influence the availability of freshwater, through the negative consequences of sea level rise and altered precipitation regimes that are changing patterns of river discharge, water level and saltwater penetration in estuaries (Dao & Suetsugi, 2014; Nguyen et al., 2008). Such changes strongly influence the quantity and quality of freshwater in estuaries and coastal rivers (Langsdale et al., 2009). Changes in the pattern of upstream flows in particular contribute to increasing uncertainty in water resources management (Dawadi & Ahmad, 2012), and have a substantial impact on regional water resources and seasonal water supplies in downstream areas (Li et al., 2010). Furthermore, rising salinity levels in rivers due to both sea level rise and declines in upstream flows can degrade of surface water supplies and impair the agricultural, industrial and urban systems which rely of them (Nguyen & Umeyama, 2011). Consequently, changing water levels driven by tide level and upstream flows frequently necessitates spatial and temporal variability in the operation of sluice gate system along estuaries (Nguyen et al., 2012). In addition, coastal areas in developing countries are typically witnessing high rates of population growth and urbanization, thereby significantly increasing water demand (Sušnik et al., 2013). The interactions between these climatic and non-climatic drivers are likely to lead water scarcity for estuarine areas in developing countries.

Assessing the vulnerability of and potential adaptation for water supply and demand systems in estuaries is necessary to meet the challenges of the current and upcoming climatic and non-climatic changes. These vulnerability and adaptation option assessments should be considered for both the water supply side and the water demand side to improve management decision and reduce the possibilities of unintended consequences of policy decision (Girard et al., 2015; Kelly et al., 2013). In addition, it is necessary to apply a systematic approach to understand the dynamic behaviors of the vulnerability and potential adaptation of systems under current and projected future conditions (Girard et al., 2015). The systematic assessment will help decision-makers identify robust adaptation options for the water supply and demand systems to ensure sufficient water supply during drought and extreme conditions for the socio-economic development in the coastal areas.

Coastal water supply and demand systems, like other environment systems, comprise a wide range of complex natural and anthropogenic processes involving multiple interactions between interdependent components with many feedbacks. Therefore, dynamic simulations of water supply and demand systems provide an opportunity to investigate the vulnerability of these critical systems to scenarios that combine projected climatic and non-climatic changes. Such a holistic understanding of the temporal interactions of interdependent elements in complex systems leads to more effective learning and management (Winz et al., 2009), as well as assisting consensus building in the identification of robust adaptation options which may address both current and future conditions (Füssel, 2007). System dynamics (SD) modeling is therefore an ideal approach to understanding complex and dynamic water supply and demand systems to inform critical management decisions (Sahin et al., 2016).

In this paper, a system dynamics modeling approach was employed to assess the operational resilience of a coastal supply and demand system in Da Do Basin of Hai Phong under both current conditions and with respect to a range of projected climatic and non-climatic changes. In light of the anticipated changes in the region, the model was also used to identify potential adaptation options to safeguard the water supply system under future climatic and non-climatic threats. This basin is potentially highly vulnerable to climate change impacts due to its coastal position and high rate of population growth and urbanization (DONRE, 2014). The basin features a sluice gate system that provides freshwater as well controlling salinity from neighboring Van Uc and Lach Tray rivers to Da Do River and irrigation channel system. Consequently, this system provides an opportunity to investigate the effects of different operational responses to potential adaptation options under changing climatic and non-climatic conditions.

More specifically, a SD modeling approach was applied to investigate interactions and feedbacks between tide level, river flows, salinity, water level, population growth, and industrial and agricultural production in the coastal freshwater system in this basin. The model was then used to assess the resilience of the sluice gate system to understand how potential relative sea level rise, reduced upstream flows and salinity penetration might alter long-term freshwater supplies and subsequent management of the system. Effects on the system of changes in water demand due to population growth, and industrial and agricultural production in the basin were also considered. Potential future changes were assessed via the exploration of a range of scenarios characterized by varying degrees of relative sea level rise, upstream flows decline, population growth, per capita water consumption, and water demand for industrial and agricultural production. The assessment of vulnerability of the system can help decision-makers to identify potential adaptation options, which can then be incorporated into the SD model to assess their robustness in reducing the vulnerability of the system under climatic and non-climatic changes.

The specific objectives of this study were to: (1) enhance the understanding of the dynamic behavior of this coastal freshwater system as it responds to changes in its key climatic and non-climatic drivers and; (2) analyze plausible future scenarios to identify which factors and interactive effects are likely to be the most influential drivers on the operational resilience of the coastal freshwater system; (3) identify and assess potential adaptation options for the system in response to future climatic and non-climatic changes. Ultimately, the SD model was developed to provide a learning tool for decision-makers to inform adaptation decision-making.

2. Study context

This study concerns the Da Do Basin in Hai Phong, a coastal city in the Red River Delta in the North Vietnam. The Da Do Basin is the largest area of the city (Figure 1) with a population of 605,000 people and an average population density of 1,075 people/km^2 (HPSO, 2015). The basin provides freshwater for five districts in Hai Phong (An Lao, Kien Thuy, Kien An, Duong Kinh and Do Son). Population growth coupled with high rates of industrialization and urbanization are expected to lead to water shortages, possibly constraining socio-economic development for the coastal city over the coming decades (DONRE, 2014).

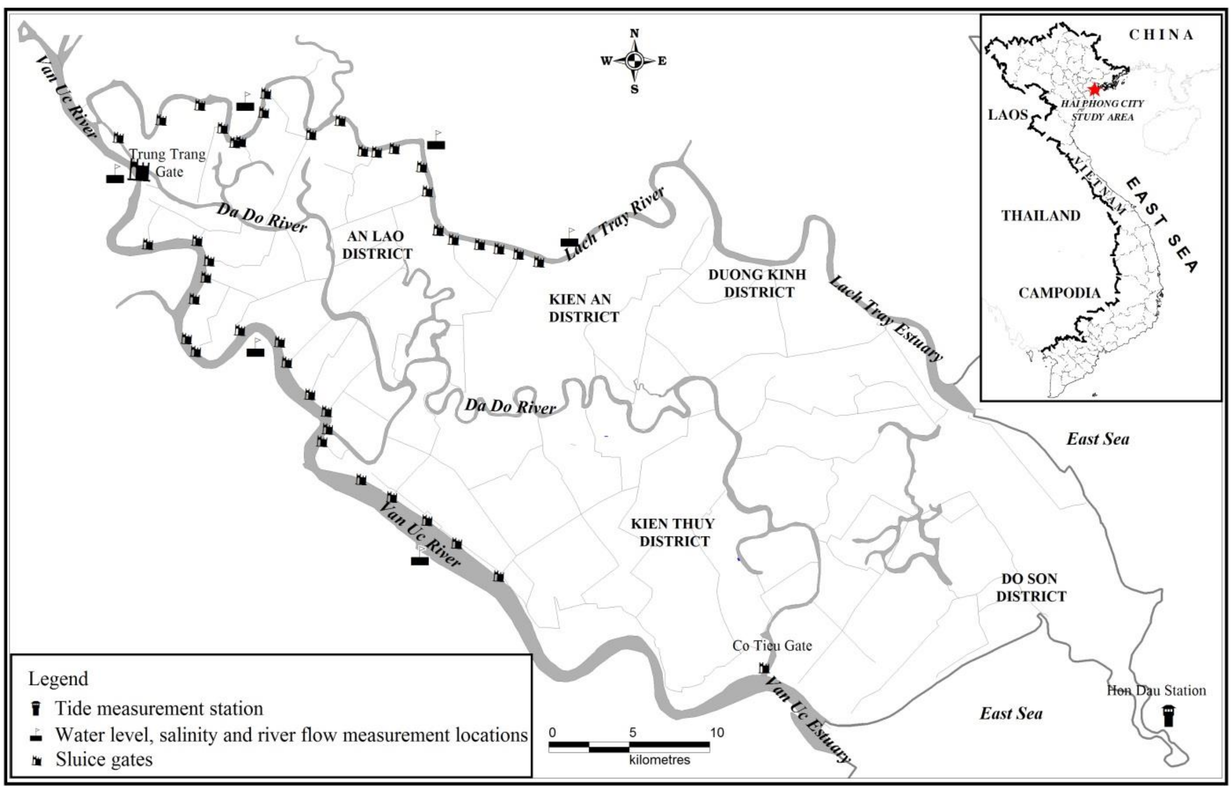

Figure 1: Da Do Basin, Hai Phong City, Vietnam

Hai Phong city is a flat and low-lying area with a mean elevation of around 1-1.5m above sea level (DONRE, 2014). Consequently, tidal influences extend a considerable distance inland. In

Van Uc and Lach estuaries, seasonal hydrological patterns depend on both riverine and marine conditions and are therefore shaped by seasonal precipitation, river flows and tide range. This region is affected by a diurnal tide – only one high and low tide each day. Historical data analyses indicate that the highest monthly sea level occurs between November and January while the lowest level occurs between March and April. In contrast, the highest monthly river flows happens between July and August and the lowest between December and April. As a result, the highest salinity levels and lowest water levels typically occur during the dry season (December to May).

The Da Do Basin is bounded by the Van Uc and Lach Tray rivers, both of which connect directly to the sea and therefore, contain tidal waters moving upriver to meet freshwater flowing downriver. There are 21 and 20 sluice gates (Pham, 2014) located along the Van Uc and the Lach Tray rivers, respectively (Figure 1). These sluice gates to supply freshwater from the Van Uc and Lach Tray rivers to the Da Do River and its connected irrigation channel system. The flow capacity of sluice gates which supply the Da Do River and irrigation channel system from the Van Uc and Lach Tray rivers are shown in Table 1. The Trung Trang gate is the largest gate in the system and controls the main freshwater input to the Da Do River. The other sluice gates are much smaller and provide freshwater only for irrigation channel systems. These gates have been divided into three ranges (Table 1) based on measurement locations of water level and salinity as well as similarity of topography in each range.

Table 1: Sluice gate flow capacities and ranges along the Van Uc and Lach Tray rivers

Van Uc River			Lach Tray River		
Sluice gate	Flow (m^3/s)	Range	Sluice gate	Flow (m^3/s)	Range
Trung Trang	139.28	Range I 30 to 40km	Goc De	3.94	Range I 32 to 40km
Tan Hung	6.89		Thuong Trang	3.05	
Tao	4.13		Cau	14.47	
Ngo	4.13		Hang La	2.54	
Nghe	4.57		Hoa Dai	6.89	
Muoi	5.17		Song	3.55	
Cat Tien I	3.05	Range II 20 to 30km	Do Lai	5.17	
Cat Tien II	5.08		Hoa Giang	5.86	Range II 24 to 32km
Cau Dong	3.55		Don Cung	6.89	
Cam Van	6.89		Dong Sim	1.47	
Truc Dao	5.08		Tay	5.51	
Bach Cau	5.17		Chi Lai	3.05	
Canh Tay	4.13		Bai Nuc	1.31	

Ham Long	6.89		Bai Vet	5.17	
Dai Dien	2.94		Tham Len	3.05	Range III 20 to 24km
Cong Dun	3.05		Den Cuu	1.47	
Kim Con	30.47	Range III 15 to 20km	Lo Gach	1.63	
Cong Hau	5.17		Truong Son I	3.45	
Phuong Ha	5.17		Truong Son II	26.12	
Cao Mat	5.17		Ca So III	3.45	
Mai Duong	6.53				

The Da Do River begins at the Trung Trang sluice gate and ends at the Co Tieu sluice gate in the estuary. The Co Tieu sluice gate almost remains closed to retain the freshwater in the Da Do River and prevent saline penetration. This gate is only opened in cases of storms or heavy rain to protect the river banks. The irrigation channel systems on either side of the Da Do River also have sluice gates to retain the freshwater and similarly release water into the Van Uc and Lach Tray rivers when necessary.

Water shortages in this region are currently exacerbated by both sea level rise and declines in precipitation which together are altering river flows, water levels and saltwater penetration in these estuaries, especially during the dry season (December and May), affecting freshwater availability in Da Do River and irrigation channel systems (DONRE, 2014).

3. Methods and model development

3.1. System dynamics modeling approach

System dynamics modeling (Forrester, 1961) was developed to study the behavior of complex systems and interactions among multiple, disparate external factors in situations where stocks and flows are fundamental. An SD modeling approach can also capture time delays and internal feedback loops that alter the behavior of the system (Sterman, 2000). An SD model comprises three main components: stocks (e.g. water availability in Da Do River and irrigation channel system); flows (e.g. water flows through sluice gate systems) and converters which control flow rates (e.g. salinity and water levels). Converters link the system elements and create feedback loops which are the basic structural elements of dynamic systems, reflecting a chain of causal relations among the interacting components of a system (Sahin et al., 2016).

The SD model represents a qualitative and quantitative research method that includes system integrated analysis and simulation (Chen & Wei, 2013). The first step in any SD modeling project is to determine the system structure which consists of positive and negative relationships between variables, feedback loops, system archetypes and delays (Sterman, 2000). Subsequently, an initial working quantitative simulation model is constructed which is then modified and improved iteratively with stakeholders to gain the desired level of detail and complexity, and to closely mimic the real system under investigation to the required level of accuracy (Sušnik et al., 2012).

SD modeling combines the advantages of continuous and discrete time concepts to deal with changes over time as well as finite time intervals (Sahin et al., 2016; Sterman, 2000). In addition, the SD modeling approach facilitates an understanding of complex systems through which biophysical, hydrological and socio-economic components can be incorporated, simulated and analyzed in one comprehensive model (Sušnik et al., 2012).

3.2. Model structure

Identifying the most important driving factors in the system is a critical step as modeling all components and their interactions in the system is typically not feasible within constraints (data availability, project duration etc.). In the current study, essential variables for simulation were chosen based on a combination of consultative workshops and focus group discussions with stakeholders in Hai Phong City, in addition to a review of the local context and analysis of historical data related to coastal water supply and demand. The most important variables, identified through these approaches, were incorporated into the SD model to assess the operational resilience of the sluice gate and freshwater storage system of Da Do Basin under future climatic and non-climatic changes (Figure 2).

The balance of the coastal freshwater system in the Da Do Basin is influenced by changes in both supply and demand of water over time. Water supply is driven by water levels and salinity levels at each relevant location of the Van Uc and Lach Tray rivers as well as water level in the Da Do River and the irrigation channel system. Water level and salinity on the Van Uc and Lach Tray rivers are strongly driven by backflows (flows from the sea) and downflows (flows to the sea) which, in turn, are driven by interactions between upstream flows (and rainfall) and tide level. While tide level leads to an increase in both backflows and downflows, upstream flows result in an increase in downflows but a decrease in backflows. Downflows happen when the water level at typical location in rivers is higher than the tide level while backflows occur when the tide level is higher than the water level in rivers. Backflows result in an increase in salinity level but downflows lead to a decrease in salinity level. Backflows coupled with upstream flows lead to an increase in water levels but downflows result in a decrease in water levels along these rivers. These water levels and salinity levels are hourly altered driven by hourly changing of tide levels in the system. Upstream flows are declining and changing over time due to a decline in precipitation in the region and increased flow management for hydropower management in upstream locations (DONRE, 2014). Tide level, however, is expected to increase over time due to sea level rise. Therefore, interactions and changes in upstream flows and tide level lead to changes in the pattern of backflows and downflows, resulting in changes in water and salinity levels along Van Uc and Lach Tray rivers.

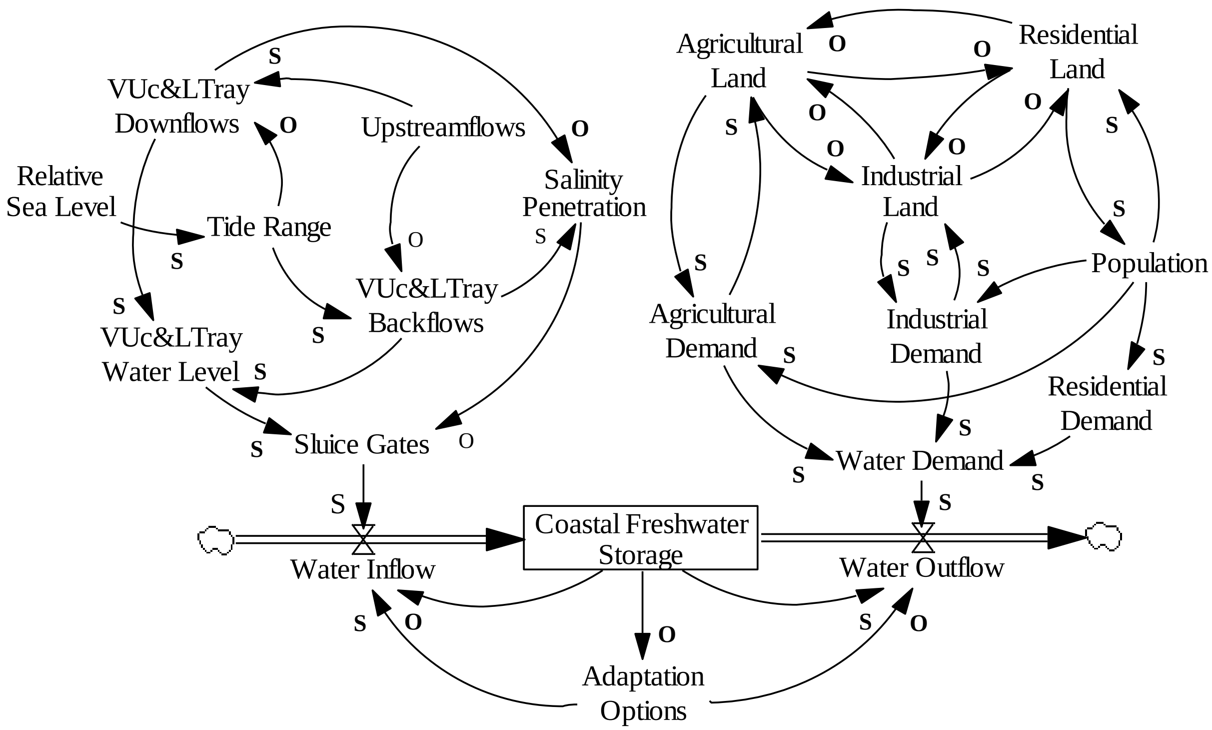

Figure 2: Schematic overview of the system dynamics model for assessing the vulnerability and adaptation options for coastal freshwater balance in Da Do Basin.

Legend: S denotes same direction, O denotes opposite direction

Water inflow through the sluice gates in this system is limited by salinity and water level, which are driven by interactions and changes among upstream flows and tide stage. Available water inflow to the freshwater system is also influenced by the operational capacity of the existing sluice gate system. The sluice gate system is intended to provide freshwater flows, and control salinity penetration from the Van Uc River and the Lach Tray River to the Da Do River, and the irrigation channel system. An opening regulation of these sluice gates was developed and strictly operated by Da Do Irrigation Management Company (Pham, 2014). These sluice gates will be opened if three conditions are satisfied: (1) water level in Van Uc or Lach Tray rivers must be more than 276cm, (2) salinity level in these rivers must be less than 1part per thousand (ppt), and (3) water level in Da Do River or Irrigation channel system must be less than 280cm.

Water demand is driven by a combination of domestic use and agricultural and industrial production at any point in time. The local context indicates 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. However, agricultural water use is likely to continue to decrease over time because agricultural land is being converted to industrial and residential land (DONRE, 2014). Interactions and changes among domestic use, agricultural and industrial production have driven variations in water demand through time.

The year 2050 was chosen for simulation because it represents a long-term perspective from which the long-term dynamic behavior of the basin and the consequences of the future scenarios could be assessed. The complete model was developed using Vensim DSS (Ventan System.inc). Hourly data (total of 4,368 hours) from a six month dry season from December 2013 to May 2014 were used to assess the balance of the coastal freshwater system in the Da Do Basin. Hourly steps are used for simulation to capture hourly changes in tide level, governing the water level and salinity, and their influences on opening the sluice gate system.

3.3. Data sources for model development and calibration

A range of historical datasets were utilized to develop and calibrate the SD model (Table 2). Water level, sea level and tide level were measured based on the National Height Datum.

Table 2: Datasets for model development and calibration

No	Data type	Period	Unit	Source
1	Sea level at Hon Dau National Station	Fifty years from 1958 to 2013	cm	National Northeast Meteorological and Weather Stations (NNMWS)
2	Precipitation at Phu Lien Station	Forty two years from 1972 to 2013	mm	NNMWS
3	Tide at Hon Dau National Station	Six months in dry season, from December 2013 to May 2014	cm	(VNODC, 2015)
4	River flows at Trung Trang Station	Six months in dry season, from December 2013 to May 2014	m^3/hour	NNMWS
5	Salinity	Six months in dry season, from December 2013 to May 2014. Measured at six locations for both Van Uc and Lach Tray	ppt	NNMWS

		rivers		
6	Water level	Six months in dry season, from December 2013 to May 2014. Measured at six locations for both Van Uc and Lach Tray rivers	cm	NNMWS
7	Sluice gate inflow system	Inflow of each gate along Van Uc and Lach Tray Rivers in current design, estimated based on water level in both sides of the sluice gates	m^3/hour	(Pham, 2014)
8	Freshwater storage system	Storage capacity of the Da Do River and Irrigation channel system in current design	m^3	(Pham, 2014)
9	Population	Population of Da Do Basin in 2014	people	(HPSO, 2015)
10	Agricultural use	Water use in dry season from December 2013 to May 2014	m^3/year	(DONRE, 2014)
11	Industrial use	Water use in dry season from December 2013 to May 2014	m^3/year	(DONRE, 2014)
12	Per capita water use	Water consumption per person in 2014	Litre/person/day	(DONRE, 2014)

3.4. Scenario design for system resilience assessment

Following the development of statistical relationships between the key variables and historical data from 2000 to 2014, a series of scenarios were simulated to understand the influences of their interactions as well as changes in climatic and non-climatic drivers to the operational resilience of the coastal freshwater system. The scenarios were used to assess the resilience of the system for the year 2050. The specific components of the system that varied across scenarios were: (1) population growth and increase in per capita water use, (2) increase in industrial water demand, (3) decline in agricultural water demand, (4) reductions upstream flows and (5) relative sea level rise. These scenarios (Table 3) were designed to reflect future conditions and to specifically understand the resilience of the sluice gate system and freshwater storage system under projected changes over the next 35 years (at the year 2050). The data input for current conditions and future scenario simulations is listed in Table 3.

Table 3: Scenarios for assessment of operational resilience of sluice gate and freshwater storage balance system

Variable	Current (2014)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Population (people)	605,000	+ 1%	+ 1%	+ 1%	+ 1%	+ 1%

Per capital water use (L/day/person)	120	180	180	180	180	180
Industrial water use (m^3/day)	50,400	50,400	+ 2.5%	+ 2.5%	+ 2.5%	+ 2.5%
Agricultural water use (m^3/day)	696,000	696,000	696,000	- 0.5%	- 0.5%	- 0.5%
Upstream flow	As water level at six locations	As current	As current	As current	*Note*	*Note*
Sea level (cm)	As tide level	As current	As current	As current	As current	+ 30cm

Note: Decrease by 15cm in upper level, by 30cm in lower level for the Van Uc River; and decrease by 10cm in upper level, by 30cm in lower level for the Lach Tray River

Scenarios of population growth, per capita water consumption increase, and changes in industrial and agricultural production (Table 3) were developed based on historical data from 2000 to 2014 in the Da Do Basin, and a study conducted by Department of Natural Resource and Environmental Management (DONRE, 2014). Scenarios of relative sea level rise and upstream flow decline were developed based on the historical data and statistical analyses.

A relative sea level rise of about 30cm by 2050 was used in this study based on a combination of historical and modeled data. Over the past 50 years, sea level at Hon Dau Station in Hai Phong area rose about 20cm (DONRE, 2014). Sea level rise projections for the region conducted by the Ministry of Natural Resource and Environment (MONRE, 2011), based on the B1, B2 and A1F1 IPCC Scenarios for Hai Phong area in 2100 projected mean sea level in the area rose by 42cm and 85cm by 2010. Relative sea level rise of 30cm will produce an increase of 30cm in the current tide level, and thus water level and salinity will also increase as a consequence. The lowest and highest levels of current tide level in the Hon Dau measurement station (Figure 1) are 30cm and 370cm, respectively (VNODC, 2015). Tide levels of 380cm, 390cm and 400cm which will follow from the 30cm relative sea level rise lay outside the range of the model calibration data. Water levels and salinity levels in these tide levels were obtained by using estimated coefficient values from simple linear regressions on historical data (e.g. salinity and water level at six locations on the Van Uc and Lach Tray rivers driven by tide level).

Upstream flows are declining and changing over time due to a decline in precipitation in the region and increased flow management for hydropower generation in upstream locations (DONRE, 2014). Scenarios for upstream flow declines were developed based on partial correlations among historical data for: (1) tide level at Hon Dau Station, (2) river flow at Trung Trang Station, and (3) water levels and salinity levels at six locations along Van Uc and Lach Tray rivers. The partial correlation analysis indicated that upper tide stage level was strongly correlated with river water level at all locations in both rivers; the correlation was much weaker between lower tide level and river water level (Figure 3 & 4).

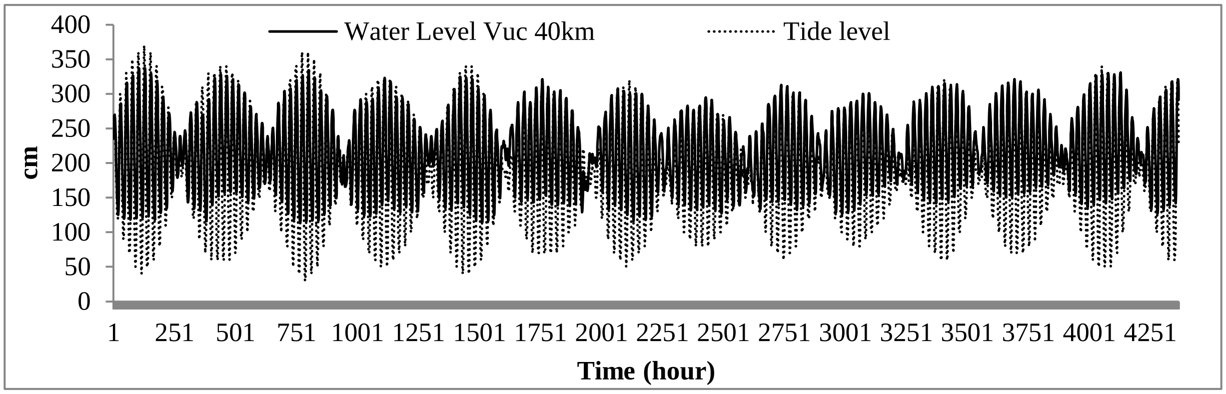

Figure 3: Relationships between tide level and water level in Van Uc River

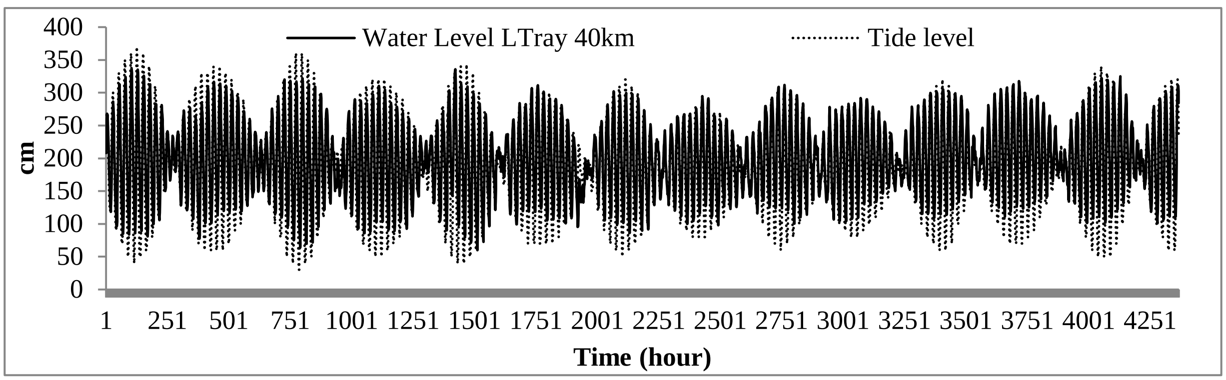

Figure 4: Relationships between tide level and water level in Lach Tray River

Overall, the correlation analysis identified strong correlations between river water level and tide level, and between salinity and tide level, even 40km upstream from the river mouths. An increase in tide level results in a rise in water level and salinity, and vice versa. The strength of this correlation varies with tide level (Figure 3 & 4). Although tide level drops to 30cm, water levels at 40km from the river mouth still remain at more than 60cm in the Lach Tray River and at 113cm in the Van Uc River (Figure 3 & 4). This is because upstream flows contribute to these water levels. Consequently, upper cycle water levels appear to be more strongly controlled by tide level while, lower water levels are more strongly controlled by upstream flows. Although upper cycle water levels are more tightly coupled with tide level, they are also partially influenced by upstream flow, because these levels are a result of combining backflows from the sea with downflows from upstream. The Van Uc River is larger than the Lach Tray River, and thus receives more upstream flows. Lower cycle water levels of the Van

Uc River are also higher than lower cycle water levels of the Lach Tray River (Figure 3 & 4). On the basis of this correlation analysis, future scenarios in the simulations which include reductions in upstream flows use upper cycle water levels and lower cycle water levels which decrease by 15cm and 30cm, respectively, from current for the Van Uc River, and by 10cm and 30cm, respectively, from the current for the Lach Tray River.

A decrease in lower cycle water levels of 30cm in the Van Uc and Lach Tray rivers will result in backflow occurring sooner in the tide cycle. Salinity rises rapidly once backflow begins (Figure 7). Consequently, salinity will also be higher when water levels along these rivers decrease following a decrease in upstream flows.

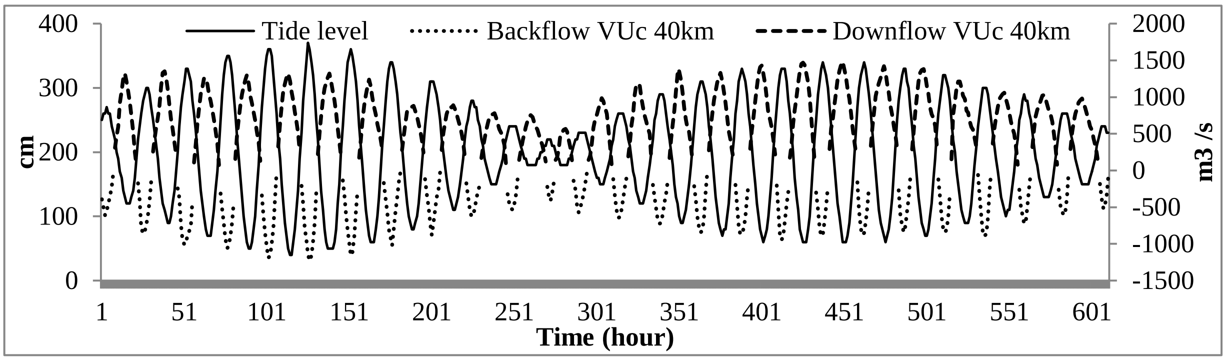

Figure 5: Relationships between tide level and backflows, downflows

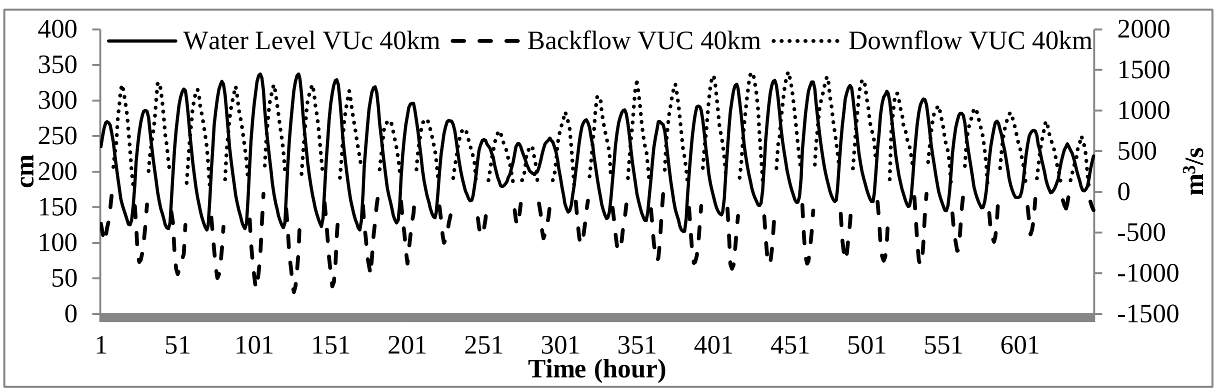

Figure 6: Relationships between river flows and water levels

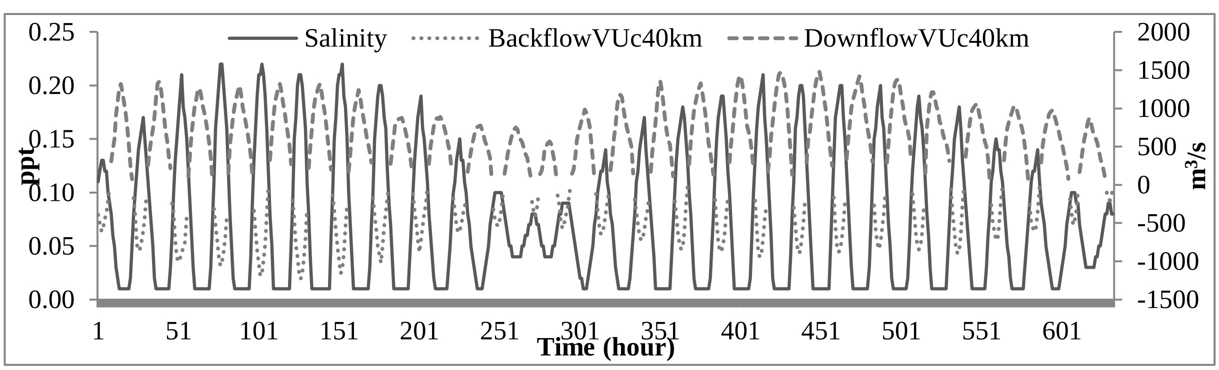

Figure 7: Relationships between river flows and salinity

3.5. Potential adaptation options

It was not possible to include all potential adaptation options identified during workshop discussions into the SD model because it was likely to be difficult to adequately quantify some options, especially with regards to their outcomes, feasibility and the availability of appropriate data to inform them. Consequently, a multi-criterion approach was used to identify the most appropriate adaptation options for incorporation into the SD model. Five criteria were used to rank alternative adaptation options, as follows (1) feasibility, (2) effectiveness, (3) sustainability and (4) data availability. Each stakeholder group discussed and scored each adaptation option from 0 to 9 against the five criteria. The scores for all five criteria were then weighted equally and summed across groups to produce an overall multi-criteria result. Three adaptation options which had the highest marks were identified and taken forward for subsequent incorporation into the SD model to assess their effectiveness in preventing the collapses of the coastal freshwater system in dry season under climatic and non-climatic changes. These adaptation options (Table 4) are (i) increasing Da Do River storage, (ii) building pumping stations, and (iii) increasing water price for residential use and industrial production. Furthermore, two combined adaptation options considered were (vi) increasing Da Do River storage and increasing water price, and (vii) building pumping stations and increasing water price to simultaneously assess their effects on both water supply and water demand sides of the system.

Table 4: Description of five adaptation options for a coastal water supply and demand system under climatic and non-climatic changes

Adaptation option	Description
Pumping stations + Water price	This adaptation option combines both building pumping stations to increase water availability in the Da Do River and increasing water price for domestic and industrial uses
Pumping stations	Building two pumping stations at Bat Trang and Quang Hung to take freshwater from the Van Uc at 38km from the river mouth to Da Do River with capacity of 112,000 m^3/hour
Water price	Increasing water price of 20% from the current prices for residential use and industrial production.
Da Do Storage	Increasing the water capacity for the Da Do River from 11,680,000 m^3 to 13,380,000 m^3, by raising the height of the current river banks by 40cm and upgrading some sluice gates
Da Do storage + Water price	This adaptation option combines both increasing Da Do storage and increasing water price for domestic and industrial uses

The ultimate aim of these adaptation options is to maintain the balance of the coastal freshwater system by maximizing the availability of freshwater and minimizing the volume of water being used from different sectors. The abovementioned adaptation options clearly aim to achieve this goal, as increasing Da Do River storage or building pumping stations are all potential adaptation options for increasing freshwater availability. Conversely, increasing the price of using freshwater, to limit water use from residents and industrial production, are potential measures to decrease water demand.

Two pumping stations are designed to take water from Van Uc River to Da Do River when Trung Trang Sluice Gate could not open due to low water level. These pumps will be operated once they satisfy three conditions: (i) Trung Trang Sluice Gate is close; (ii) Water level at 40km from the Van Uc River mouth is larger than or equal to 200cm, and (iii) salinity at 40km from the Van Uc River mouth is less than 1ppt. In addition, increasing Da Do River storage is supposed by increasing 40cm of river banks and these increased numbers were added into the storage water level in the SD model to assess the effects of increasing Da Do River storage.

It is supposed that increasing water prices of 20% for domestic use and industrial use would result in expenditure changes for both residential consumption and industrial production. The price of water sold by Water Supply Joint Stock Company in 2015 was $0.45/m^3 for residential use and $0.95/m^3 for industrial production (WSJSC, 2015). The cost of increasing water price and its effect on water use of domestic use and industrial production is estimated by calculating the decreased volume water uses driven by increasing water price shown by the following equations.

$$Pn = Pc \; x \; \%Change \; in \; price \quad (1)$$

$$Qn = Qc \; x \; \%Change \; in \; water \; use \quad (2)$$

$$\%Change \; in \; water \; use = \beta p \; x \; \%Change \; in \; price \quad (3)$$

Where: Pc = current water price; Qc = current quantity of water use; Pn = new water price; Qn = new quantity of water use, βp = price elasticity

An average value of price elasticity was selected for residential use and industrial production after conducting a critical literature review. The price elasticity for residential use is estimated at around -0.5 (Hoffmann et al., 2006; Hung & Chie, 2012; Olmstead et al., 2007; Ruijs et al., 2008) and for industrial production is estimated at around -0.3 (Dharmaratna & Parasnis, 2010; Malla & Gopalakrishnan, 1999; Schneider & Whitlatch, 1991; Williams & Suh, 1986). These values were used to estimate the annual increased expenditure of increasing water price 20% for both domestic use and industrial production (Table 5).

Table 5: Decrease volume water uses driven increasing water price 20%

Water use sector	Current price ($/m^3)	Current water use (1,000m^3)	New price ($/m^3)	New water use (1,000m^3)	Water decline after increased price (1,000m^3)
Residential use	0.45	16,893	0.54	10,136	6,757
Industrial production	0.95	9,173	1.14	3,302	5,871
Total		26,066		13,438	12,628

3.6. Model testing, sensitivity and verification

In addition to directly incorporating historical data on water level, salinity, domestic use and agricultural and industrial production in six month dry season (Table 2) into the these variables in the SD model, the opening hours of sluice gates along the Van Uc and Lach Tray rivers were selected to test the accuracy of the model. The opening hours of sluice gates are one of the most important indicators for the performance of the model because the gates can be opened if they satisfy conditions of both sides of the gates: water level and salinity in the Van Uc and Lach Tray rivers, and water level in the Da Do River and irrigation channels. The water level and salinity in the Van Uc and Lach Tray rivers are strongly driven by tide level and upstream flows. The water level in the Da Do River and irrigation channels is strongly driven by water uses from residents, industrial and agricultural production.

A statistical measure of coefficient of determination (R^2) (Steel & Torrie, 1960) was used to measure the agreement between the observed data and the simulation values of the opening hours of sluice gates. R^2 indicates the proportion of the variance in measured data explained by the model. The values of R^2 ranges from 0 to 1, in which values closer to 1 indicates the model simulates the system well, and the equation for calculating R^2 is as follows

$$R^2 = \left(\frac{Cov(O,S)}{\sigma O\ \sigma S}\right)^2$$

where O and S are the observed and simulated values of the tested variables; Cov (O,S) is the covariance of values with respect to the observed or simulated values, and σO and σS are the standard deviation of the two sets of values (Safavi et al., 2015).

Sensitivity analysis was also performed to obtain more confidence around the dynamic behavior of the model, and to evaluate the impact of parameter uncertainty on the water availability in the system. In addition, the aim of sensitivity analysis was to identify which variables have the greatest impact on the dynamics behavior of the model, thereby guiding decision-makers to develop a future policy management (Sušnik et al., 2012). In this study, water level, salinity, and domestic water use, agricultural and industrial water demand were used as main variables which their values were individually varied by ±10%, and holding other remaining input variables constant at their base case values to understand the behavior of the SD model (Maani & Cavana, 2007). The changes in water volume in the system over six month dry season were recorded for each variation of the parameters, and then were used to identify which variables have the most influence on the water availability in the system.

The SD model was further revised and validated by consultative processes involving a range of climate change and water experts in Hai Phong City as well as managers and practitioners of Da Do Irrigation System Management Company. Several workshops and focus group discussions were held in Hai Phong City in 2015 and 2016. Stakeholders participated in developing causal loop diagrams and validating the accuracy of the model to appropriately reflect the current situation and future prediction of the coastal freshwater system. More specifically, stakeholder consultation was used to assess the validity of model components by seeking agreement about input data validity, relationships among variables, and model logic which adequately reflects the real situation. Consensus was reached among the participants in the workshops to the point that they agreed with the results of the model and were confident that the model could be used to develop resilient policies and identify effective and efficient adaptation options to secure freshwater demand for all activities in Da Do Basin and adjacent areas under the future scenarios.

4. Results

4.1. Model testing, sensitivity analysis and verification

The results of the model testing are shown in Figure 8. The simulated results followed the same trend as the observed data, indicating that the opening hours of sluice gates almost satisfactorily fit the observation data. The values of R^2 (Table 6) range from 0.78 to 0.93 indicating that model replicates from a moderate to good fit of opening hours of sluice gates which were affected by water level and salinity. Trung Trang gate is the most important gate in the system as it provides a major water supply for all activities in the basin. The statistical analysis shown that the opening hours of Trung Trang gate between observed values and simulated values are well calibrated with the highest value of R^2 (0.93).

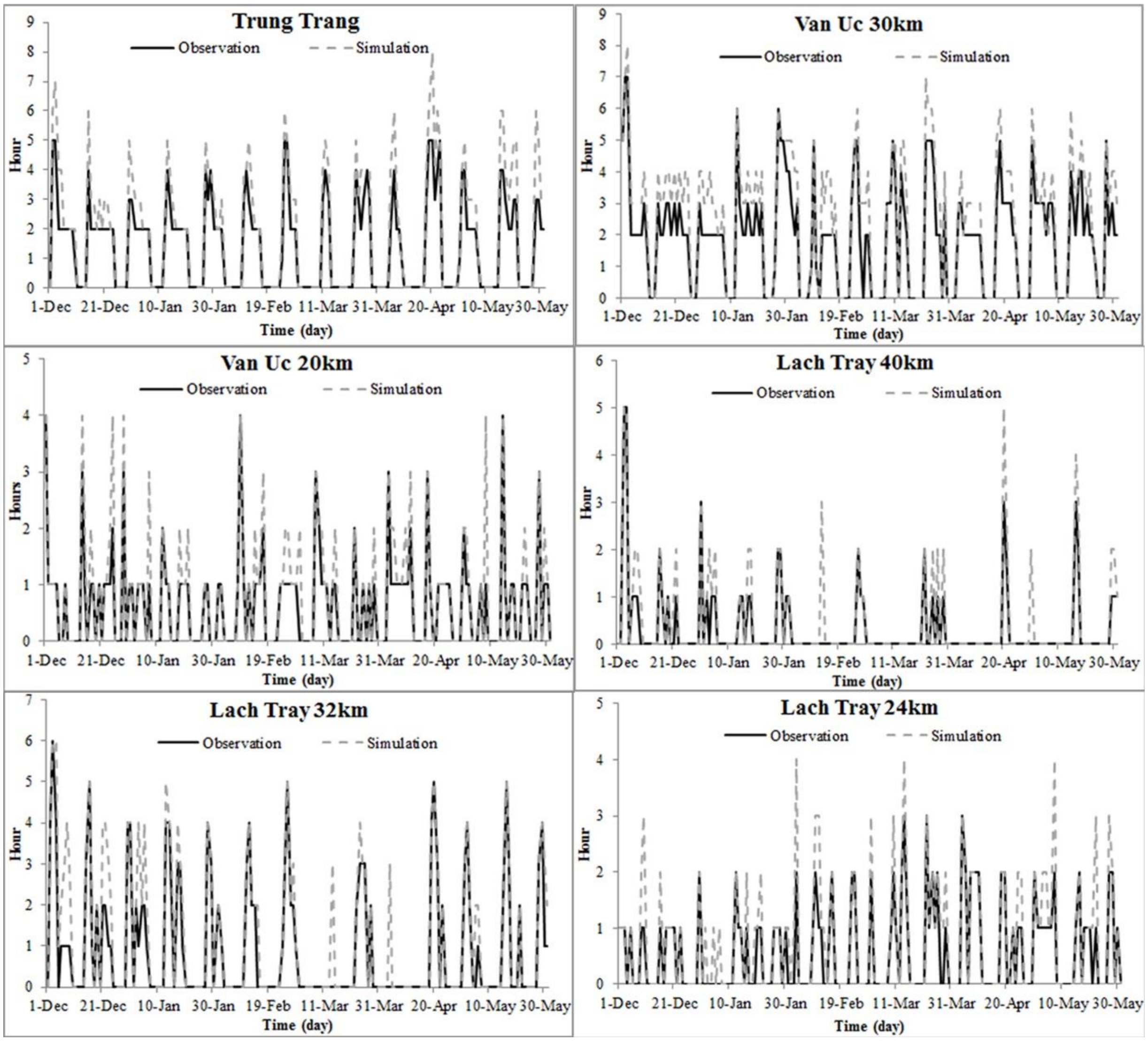

Figure 8: Observation and simulation of opening hours of sluice gates in Van Uc and Lach Tray rivers

The low value of R^2 for the sluice gates in the Lach Tray River could be attributed to the uncertainty driven by a high complexity in the system (e.g. local precipitation, water level and salinity as well as operational management of sluice gates). However, many system dynamists have concluded that the aim of the SD model is to understand the dynamic behavior patterns of the system over time, and not designed to make accurate predictions of system variables (Forrester, 1961; Sterman, 2000).

Table 6: Statistical results for opening hours of the sluice gate system

Sluice gate	Trung Trang	Van Uc 30km	Van Uc 20km	Lach Tray 40km	Lach Tray 32km	Lach Tray 24km
R2	0.93	0.87	0.82	0.79	0.81	0.78

The results of sensitivity analysis for freshwater storage balance are shown in the Figure 9. Water level and salinity had the most influence on the freshwater storage balance in the system. According to a criteria proposed by Maani and Cavana (2007), water level had high sensitivity (>35% change), salinity had moderate sensitivity (15 – 34% change) and all agricultural water use, domestic water use and industrial water use had low sensitivity (5 to 14% change) to the freshwater storage balance.

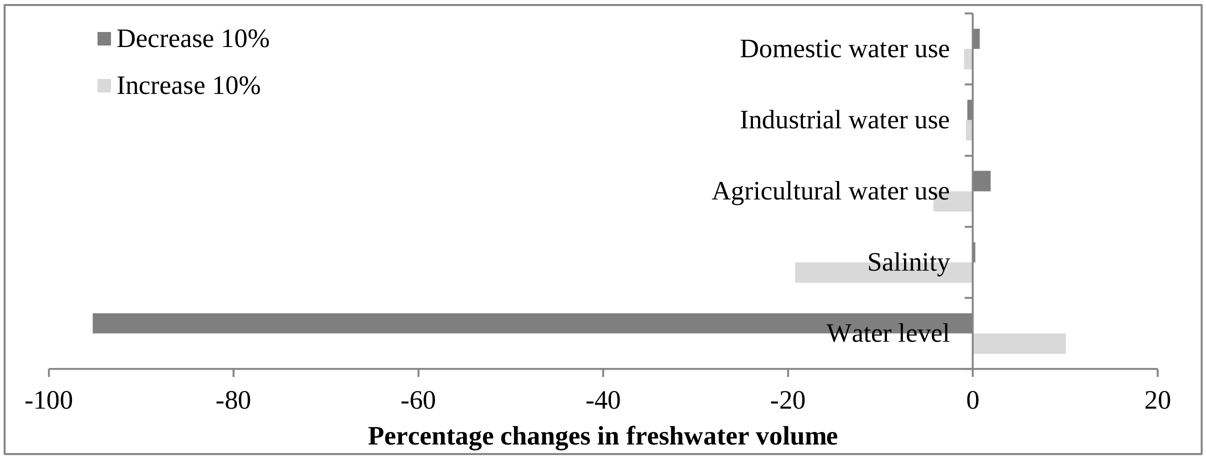

Figure 9: Sensitivity analysis results for freshwater storage balance in the system

4.2. Changes to freshwater storage balance under future scenarios

Model results for the current condition indicate that current operation of the sluice gates and the freshwater storage system satisfy water demand from domestic, agricultural and industrial water uses. The current availability of freshwater in the system is about 19 million m^3/hour (Figure 10). This water availability is considered as business as usual (BAU), and can be used to assess the operational resilience of the sluice gate and freshwater storage system to climatic and non-climatic changes. The operational resilience of the system is assessed to examine which drivers seriously deplete freshwater availability in the system by conducting a series of additional simulations for five mixed scenarios. Freshwater availability in the system under the five mixed scenarios is shown in Figure 10.

Under population growth and increased per capita water use (Scenario 1) and increased industrial production (Scenario 2), as well as declining agricultural use (Scenario 3), water availability falls below current, and would not be sufficient to meet the demand from domestic, industrial and agricultural uses in the latter months of the dry season. In addition, when upstream flow decline (Scenario 4) was introduced, the freshwater storage system essentially collapses. However, if a relative sea level rise of 30cm (Scenario 5) is also introduced, the system only collapses in the later months of the dry season.

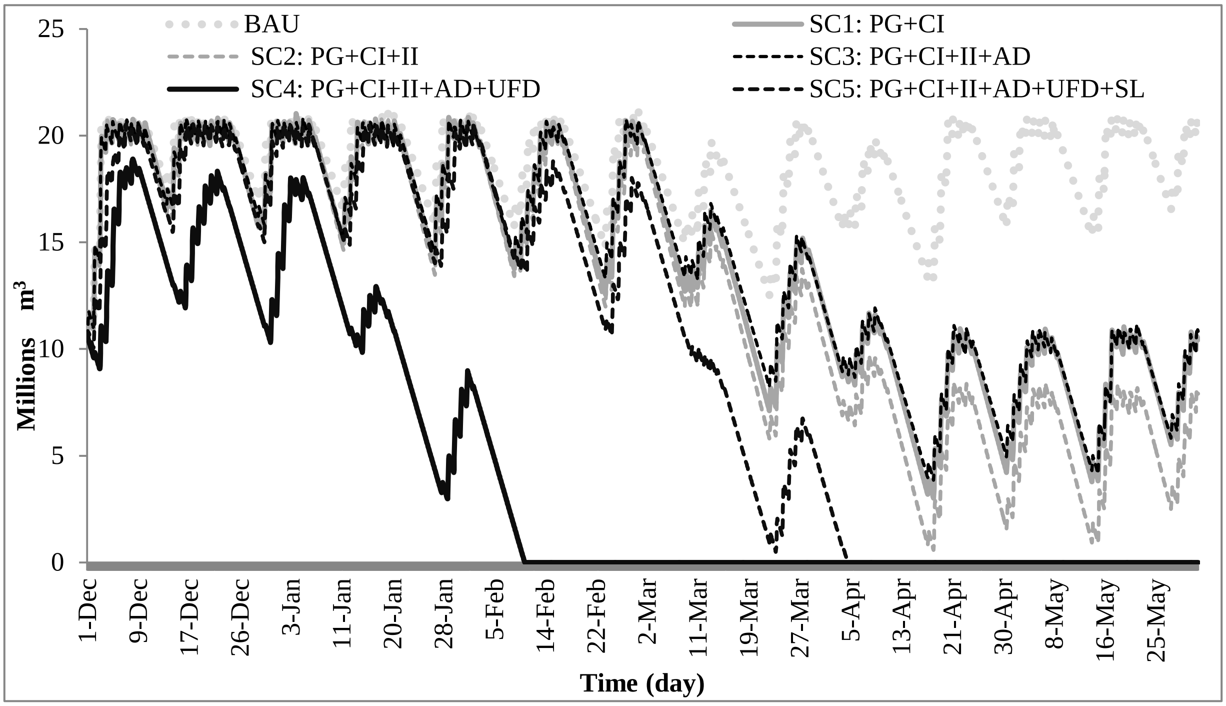

Figure 10: Freshwater balance system in the dry season under BAU and future scenarios

Legend: PG: Population growth, CI: Capita use increase, II: Industrial use increase, UD: Upstream flows decrease, AD: Agriculture use decrease, SLR: Sea level rise

It is worth noting that average salinity level at 40km from the river mouths increases by 0.05ppt from 0.08ppt to 0.13ppt in the Van Uc River, and by 0.07ppt from 0.10ppt to 0.17ppt in the Lach Tray River between BAU and the UFD & SLR scenario. However, this increased salinity is still well below than 1ppt threshold for sluice gate opening on both rivers. Thus, Trung Trang, the largest gate in the system is still able to supply freshwater to the Da Do River which then supplies all activities in the basin. Although, sluice gates located at 32km in Lach Tray River and less than 24km in both Van Uc and Lach Tray rivers were completely closed under the UFD and UFD&SLR scenarios, water availability in the system still collapses in the later months of the dry season.

In addition, water levels at 40km from river mouths of both rivers also differ between the BAU and SLR scenario. Comparing the SLR scenario with BAU, water level at 40km from the mouths of the Van Uc and Lach Tray rivers increases by 8.5% and 12.9%, respectively, under SLR. Therefore, the number of hours during which water level satisfies the condition for opening sluice gates (>276cm) increases by 88% and 85%, respectively, for the Van Uc River and Lach Tray River. Consequently, the sluice gates in this section of the system for both rivers can be opened for more hours under the SLR scenario. This again helps to ensure freshwater availability, such that the storage system only collapses in the later months of the dry season.

4.3. The freshwater balance system under adaptation options

Under all scenarios of climatic and non-climatic changes, the effectiveness of these six adaptation options was illustrated as Figure 11. The most effective adaptation was pumping stations + increasing water price, followed by pumping stations, increasing Da Do River storage + increasing water price, increasing Da Do River storage, and increasing water price. Construction of pumping stations and increasing water price both individually and in conjunction are only two adaptation options which could recover the collapse of the system under climatic and non-climatic scenarios. Although, increasing Da Do River storage + increasing water price or increasing Da Do River storage can recover some later months in the dry season, several days of this period are still collapsed.

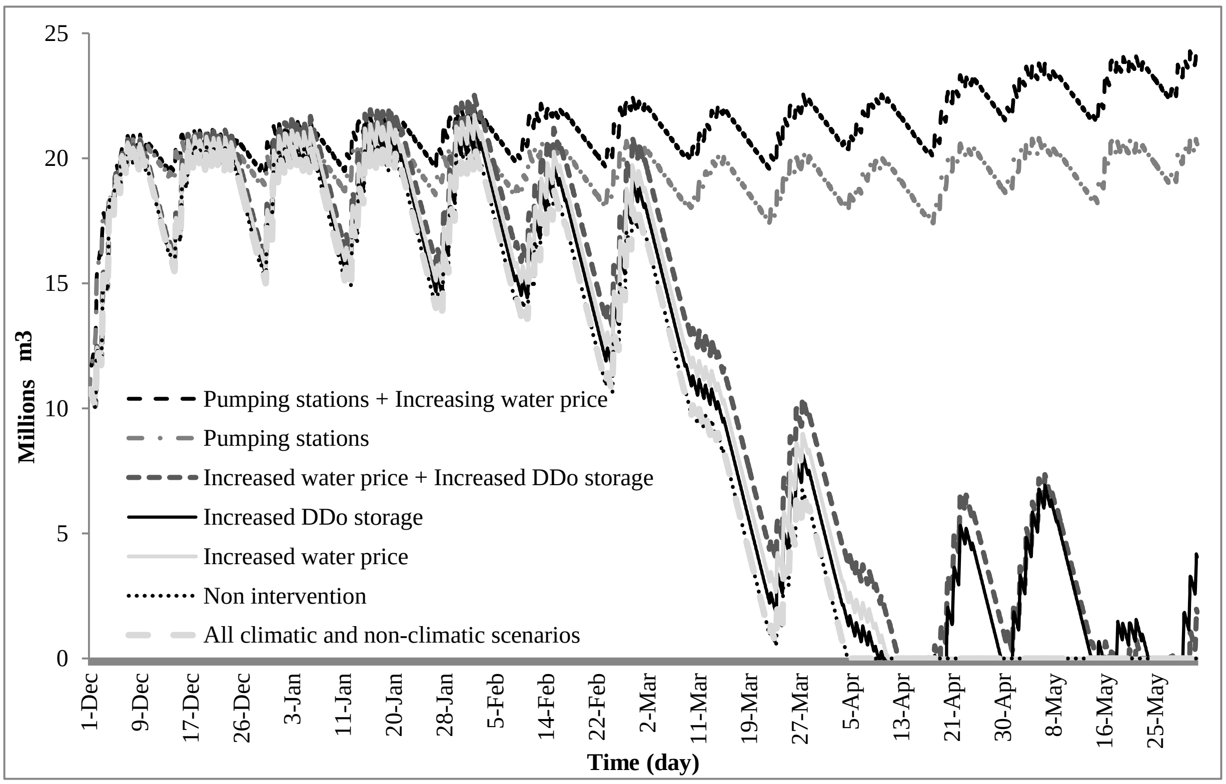

Figure 11: The freshwater balance system under scenario 5 and adaptation options

5. Discussion and conclusions

Climate change can be expected to significantly influence the dynamics and complexity of managing coastal freshwater systems, largely as a result of altered seasonal precipitation patterns and rising sea levels. Such changes in turn are very likely to alter patterns of river flows as well as the frequency, duration and extent of marine-derived saline water penetration in estuaries (Peirson et al., 2015). In this SD model, a relative sea level rise of 30cm produces salinity increases of 25% and 30% at 40km from the mouths of the Van Uc and Lach Tray rivers, respectively. Furthermore, when upstream flow decline was modeled in addition to relative sea level rise, salinity at 40km increased by 62% and 70%, respectively for the Van Uc and Lach Tray rivers. These results are similar to those produced by Nguyen and Umeyama (2001) for the Tra Ly, Ninh Co and Day estuaries which are close to the Da Do Basin. Although salinity is predicted to increase significantly following 30cm of relative sea level rise, crucially, salinity levels still remain below 1ppt at 40km from the river mouths. This means that the amount of hours for which the Trung Trang sluice gate – the key freshwater supply gate in the system – can be opened is not adversely affected by 30cm of relative sea level rise in combination with reduced downstream flows.

The scenario simulations conducted in the current study demonstrate that upstream flow decline is likely to be the most influential factor affecting operational resilience of the coastal freshwater system in the Da Do Basin. Upstream flow reductions could be driven by climate change, especially a gradual decrease and change in precipitation, coupled with increased temperature (Dawadi & Ahmad, 2012). In the dry season, precipitation has decreased over 55 years in the Hai Phong region and in its upstream areas. Flow reductions will also be exacerbated by human activities altering flow regimes. Several dams for hydropower are located upstream of Hai Phong City in Vietnam and in China, and the operational management of these dams could significantly influence river flows in the Hai Phong region. These hydrological changes, coupled with anticipated sea level rise, can be expected to result in altered patterns of river discharge and water level, therefore, increased salinity penetration in the estuaries, with significant implications for the freshwater system in coastal areas (Nguyen et al., 2012), including a decline in the quantity and quality of water available for urban, industrial and agricultural uses.

Simulation results of scenarios and the five adaptation options from the SD model can be used to inform water management decisions in the Da Do Basin by contributing to the identification of effective and efficient adaptation options for better securing adequate freshwater to meet the growing water demands in the basin. The five adaptation options assessed here were identified by stakeholders and the effectiveness of these adaptation options was assessed in the SD model. The assessment of adaptation options indicated that building pumping stations and increasing water price would be urgent requirements in the Da Do Basin to meet the growing water demand in the near future, as a result of population growth, and associated industrial development. In addition, there is a plan to transfer freshwater from the Da Do Basin to other areas in the region, i.e. Cat Hai and Cat Ba Island (DONRE, 2014). At the same time, the availability of water supplies in this basin is highly likely to decline due to rising sea levels, and declining precipitation and upstream flows.

During past decades, water resource management has focused mainly on assessing water supply or water demand separately (Dawadi & Ahmad, 2012). Consequently, the many interactions and relationships between hydrological and socio-economic aspects of water resource systems have rarely been taken into account (Qin et al., 2011), especially with respect to analyzing long-term scenarios regarding these interactions. Such disjointed analyses could, inadvertently result in inappropriate and/or unsustainable decisions regarding water resource management. More recently, scholars have sought to assess water supply and demand simultaneously. However, there remains a paucity of knowledge with regard to understanding the multiple interactions and relationships among sea level rise, upstream flow regimes, estuarine salinities, population growth and socio-economic development, and their combined effects on the operational resilience of sluice gate management in coastal freshwater storage systems. The current study has demonstrated the efficacy of SD model in assessing the vulnerability of a coastal freshwater system in a developing country by investigating all of these factors and their interactions. The modeling approach presented here and the key finding regarding the significance of upstream flow decline are likely to be highly applicable to other basins in Hai Phong City as well as in estuarine settings in other developing coastal cities where water resource management is vulnerable to relative sea level rise and upstream flow decline, and pressures from socio-economic development.

The involvement of stakeholders in the development and validation of the models was an important element of the process as it ensured appropriate reflection of the real world conditions in the basin. The validity of the SD model was revised iteratively and validated by stakeholders' experience and knowledge of system behavior and management to increase the feasibility of the model. Once the validity and representativeness of the SD model had been established through stakeholder involvement, the model was then applied to facilitate discussions about effective adaptation options that were assessed in the SD model. The aim of these adaptation options is to effectively and efficiently secure freshwater against a background of an expanding population, and changes in industrial and agricultural production in a future climate changes.

A key limitation of this study concerns the development of future scenarios based on historical data because past relationships between variables as well as the variables themselves, may shift in relation to climate change and other pressures. Modeling the influences of the interaction between tide level and river discharge on water level and salinity along these estuaries is particularly challenging. These interactions form a complex and dynamic system which is strongly driven by sea level rise and upstream flow decline. In this study, future scenarios of relative sea level rise and upstream flow decline were developed by using results from partial correlations and simple linear regressions among tide level, river flow, water level and salinity along the Van Uc and Lach Tray rivers. Although these analyses provide an indication of future conditions and outcomes, further investigation of the interactions between these variables and the uncertainties which surround them, would greatly improve the capacity of this model to forecast system operation under future scenarios.

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