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Assessment of the vulnerability of a coastal freshwater system to climatic and non-climatic changes: A system dynamics approach

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ABSTRACT

Water resources management faces many challenges in coastal areas of developing countries, where climate change coupled with high rates of population growth and urbanization have the potential to cause severe water scarcity. Of particular concern, are sea level rise and altered precipitation regimes that will influence spatial and temporal patterns of river discharge, water levels and saltwater penetration in estuaries. A sound understanding of factors affecting the vulnerability of coastal freshwater systems is therefore needed to mitigate the potential impacts of climatic and non-climatic changes. In this study, a system dynamics modeling approach was employed to explore the vulnerability of the coastal freshwater system in Da Do Basin, Vietnam to projected sea level rise, upstream flow decline and socio-economic development. This system includes the Da Do River and irrigation channels that receive freshwater through sluice gates from the Van Uc and Lach Tray rivers. The model was developed as a learning tool for decision-makers to improve their understanding of the spatial and temporal dynamic behaviors of the system and to inform adaptation decision-making by allowing exploration of plausible future scenarios. The model was developed, calibrated and validated using both historical data and expert knowledge elucidated via stakeholder consultation. Model results indicate that under current conditions, freshwater availability is sufficient to meet existing domestic, industrial and agricultural demands. However, the coastal freshwater system changes significantly and collapses under several plausible future scenarios. Future projections suggest that declining upstream flows will be the strongest threat to the system's vulnerability. System dynamics models enable consideration of the interactive effects of a range of climatic and non-climatic drivers on water resources availability thereby facilitating improved planning for collective and proactive adaptation actions to efficiently secure freshwater resources to support socio-economic development of coastal basins in the face of climate change.

1. Introduction

Coastal freshwater supply and demand systems comprise a wide range of complex natural and anthropogenic processes involving multiple interactions between interdependent components with many feedbacks. Water supply is particularly affected by climate variability and climate change with sea level rise, and altered precipitation regimes (IPCC, 2013) influencing temporal and spatial patterns of river discharge, water levels and saltwater penetration along estuaries (Nguyen et al., 2008). Changes to upstream flow regimes, for instance, can have a substantial impact on regional water resource and seasonal water supplies in downstream areas (Zhou et al., 2017). Rising salinity levels in rivers due to both sea level rise and declines in upstream flows can degrade surface water supplies and impair the agricultural, industrial and urban systems which rely on them (Nguyen and Umeyama, 2011). Spatial and temporal variation in water and salinity levels driven by tide level and upstream flows often necessitate spatial and temporal changes to the operation of sluice gates along estuaries which supply freshwater to agriculture, industry and households (Nguyen et al., 2012). In contrast to water supply, water demand is driven largely by population growth, economic development and land use change

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(Sušnik et al., 2013). The interactions among these drivers are widely considered to be the main factors contributing to a growing gap between water supply and demand in many locations around the world (Dawadi and Ahmad, 2013). Water scarcity is especially prevalent in coastal areas of developing countries, where high rates of population growth and urbanization are typical.

Overall, the vulnerability of coastal freshwater systems over time is determined by changes in these major climatic and non-climatic factors. Understanding the dynamic balance of coastal water supply and demand systems therefore relies on knowledge of the temporal and spatial variations in these drivers as well as their interactions. 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 among 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 address both current and future conditions (Füssel, 2007). System dynamics (SD) modeling thus provides an ideal approach for understanding complex and dynamic water supply and demand systems to inform critical management decisions (Sahin et al., 2015).

Here, we demonstrate an SD modeling approach to assessing the vulnerability of a coastal freshwater system in the Da Do Basin in Hai Phong, Vietnam under current conditions, and with respect to projected climatic and non-climatic changes over time. This basin is potentially highly vulnerable to climate change impacts due to its coastal position and its high rate of population growth and urbanization (DONRE, 2015). The basin features a sluice gate system that supplies freshwater to the Da Do River and irrigation channels as well controlling salinity ingress from the neighboring Van Uc and Lach Tray rivers. Consequently, the Da Do Basin provides an opportunity to investigate the effects of different operational responses (i.e. spatial and temporal variation in opening and closing of sluice gates) to changing climatic and non-climatic conditions.

An SD modeling approach was used 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 vulnerability 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 affect subsequent management of the system. Effects of changes in water demand due to population growth, and changes in industrial and agricultural production in the basin were also considered.

The specific objectives of this study are to: (1) enhance understanding of the dynamic behavior of this coastal freshwater system as it responds to spatial and temporal 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 damaging to the vulnerability of the coastal freshwater system. Ultimately, the SD model was developed to provide a learning tool for local stakeholders to inform adaptation decision-making.

2. Case study context

The case study for the SD modeling is the Da Do Basin in Hai Phong, a coastal city in the Red River Delta in northern Vietnam. The Da Do Basin is the largest area of the city (Fig. 1) with a population of 605,000 people and an average population density of 1075 people/km^2 (HPSD, 2015). The basin provides freshwater for five districts in Hai Phong (An Lao, Kien Thuy, Kien An, Duong Kinh and Do Son). An annual population growth (1%), 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 coming decades (DONRE, 2015).

Hai Phong city is a flat and low-lying area with a mean elevation of around 1–1.5 m above sea level (DONRE, 2015). Consequently, tidal influences extend a considerable distance inland. In the Van Uc and Lach Tray estuaries (Fig. 1), seasonal hydrological patterns depend on both riverine and marine conditions and are therefore shaped by seasonal precipitation, river flows and tide level. Analyses of climate data from National Northeast Meteorological and Weather Stations (NNMWS) indicate that the lowest monthly downstream flows and rainfall over fifteen years from 2001 to 2014 occur during the dry season, between December and May. As a result, the highest salinity levels and lowest water levels typically occur during this period, thereby causing a high potential for water

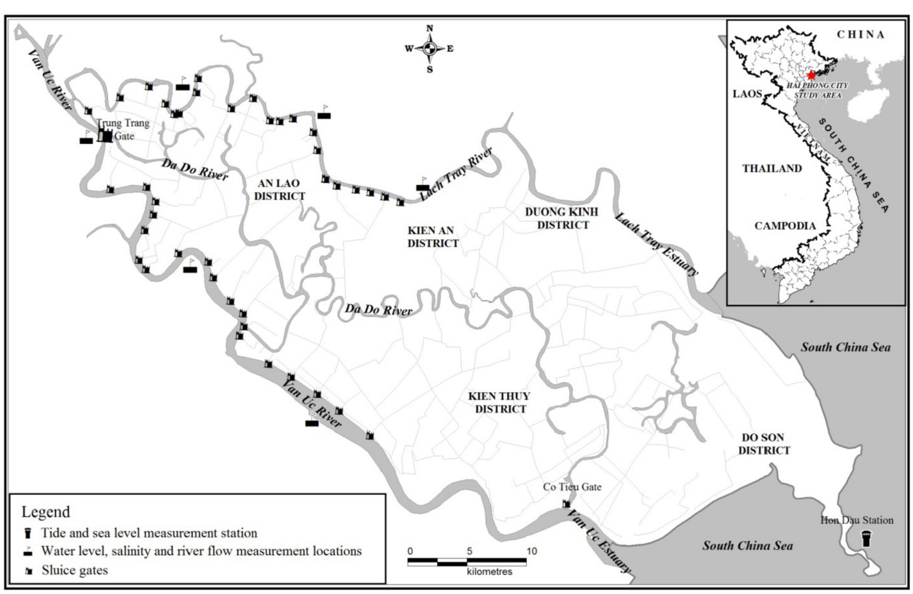

Fig. 1. Da Do basin, Hai phong city, Vietnam.