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Using System Dynamic Modeling for Improving Water Security in the Coastal Area: A Literature Review

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Abstract

BACKGROUND: Water is one of the basic materials of human existence. In respect this, many countries have been focused on water security agenda as one of the national strategic security. One of water security domains is coastal water security. Water security, due to the myriad of factors influencing water quantity and quality in coastal area, can be considered as a complex system. Due to the complexity and dynamic characteristic, system dynamic model (SDM) is needed to implement in coastal area to integrate all subsystem.

AIM: This study aims to analyse the subsystems relating to coastal water security. The subsystem determination used to develop future policy-making relating to coastal water security.

METHODS: For this purpose, a systematic literature review was conducted and a set of 12 papers was selected from 2009 – 2019.

RESULTS: The papers' analysis shows the applicability of SDM to solve complex problems. Water scarcity has been identified as a major problem in the coastal area, identified in eight papers. Three papers are related to water quality and only one paper relating to both. There are four major subsystems relating to coastal water security: environment, economic, social, and politic. Information about the aquaculture activities, the mechanism of coastal water pollution and water relating human health risk is still limited.

CONCLUSION: We recommend use of SDM in the coastal water security to be extended to aquaculture, coastal water pollution and human health risk aspect in order to promote a holistic understanding of the complex issues and to develop more effective policies.

Introduction

Many countries in the world have been focused on water security agenda as one of the national strategic securities agenda [1]. As one of the most urgent topics facing humanity in the 21st century, water security can affect people's lives, property, and ecology [2], [3], [4], [5]. As one of the basic materials in human existence, the purposes of water are to support the development of human health, economic activities, and cultural lives [6]. In the last decade, human society facing serious water problems such as water scarcity, water pollution, and especially water damage caused by floods [7].

Lack of water security will impact to individual, city, countries, region, and global, which 80% world's population will be threatened by serious problem [1], [8]. In developing countries, an estimated 1 billion people lack access to safe affordable drinking water, 2.7 billion lack access to sufficient sanitation, and millions die each year from the preventable water-borne disease [3]. Contaminated water is one of the main environmental mediums of mortality and morbidity worldwide [9], [10], and evaluation of the quality of drinking water is one of the high priorities to avoid any health problems [11].

Water security context has diverse domain such as agricultural water security, domestic water security, urban water security, coastal water security, urban water supply, and demand system security, water resources security, and integrated water resources security [2], [3], [12], [13], [14], [15], [16]. Therefore, we conclude there are three domains of water security system: (1) Water resources security which has been focused to freshwater scarcity issue, which continue to gain urgency in science and policy term, (2) water environmental security refers to protect water from degradation and pollution for guaranteeing public health to maintain a good ecological status (GES) and sustainable functioning, and (3) water disaster aims to eliminate threats of water-related hazards and water emergency to solve water damage issues [2], [13], [16].

The problems existing in current water development and utilization include water deficit, serious waste of water, deterioration of water ecological environment due to the excessive exploration of water, disrepair, and aging of small water conservancy projects, and less enough attention paid to water management [6]. The coastal region is one of the areas vulnerable to water insecurities. The aquifer in coastal areas is linked to sea; an extraction of water from the reservoir is partly balanced by influx of saline water from the sea, particularly when there is less rainfall. Saltwater can be trapped in the subsurface of sediments from floods in past, or when sea levels were higher in some coastal regions [17]. Moreover, many coastal areas have ecological pressure induced by population growth, land-use intensification, a projected warming and drying climate, an increasing likelihood of drought condition, and poor environment stewardship [18], [19], [20]. On the other hand, average global sea level is rising gradually due to global warming, which impacts to pattern water use in the coastal area [18], [21]. Furthermore, the higher content of salt in water caused the water is unsuitable for drinking or agricultural use [15], [17].

The coastal and marine environment is greatly influenced by the increase of population, rapid urbanization, tourism, aquaculture activity, agriculture, industrialization, and motorization [15], [22], [23]. Besides water scarcity, a problem facing by population in coastal area is also related to water quality. The coastal and estuary pollution has become a crisis in the natural environment because lithogenic and anthropogenic sources discharge an extensive amount of pollutants into estuaries and coastal waters. Humans can expose to xenobiotic through ingestion, inhalation, and dermal exposure [24], [25], [26].

Most of these pollutants cause serious threats for the health of marine organisms and human beings, and they cause environmental crises in marine ecosystems such as loss of biodiversity, widespread of exotic and invasive species, contamination of aquatic organisms including fish and shellfish, mortality and extinction of aquatic organisms, fecal coliform contamination, eutrophication, anoxia, bio-absorption, and bioaccumulation [26], [27], [28], [29], [30].

Coastal waters receive pollution from diverse sources, including storm drains, rivers, effluent outfall, sewer overflow, and diffuse source inputs [31]. One of the main sources of pollution in the coastal area is land-based sources include runoff pollution that enters the water supply from industrial and agricultural waste, ranches and forest areas, oil spill from vehicle engines, garbage, and sewages [27]. Moreover, air pollution and shipping activities actually will affect to some water pollution, which settles into waterways and oceans [27]. Therefore, to solve these problems, policy-makers have created integrated water management approach to integrate water supply and water demand, water quantity and water quality, surface and groundwater, and water-related institutions at municipal, local, national, regional levels are needed [32].

Due to its complexity and dynamic characteristic of a coastal area, we need a system dynamic approach to integrate all subsystem. The system dynamics model is a qualitative and quantitative research method that includes system integrated analysis and simulation [1]. Each subsystem is resulted by the interaction of numerous factors, and the uncertainty of linear and non-linear relationships among the factors will complicate the water security issue. System dynamic aims to simulate the structure of a various complex system and to analyze the internal relation of the system [1]. Besides, it also can be used to identify problem non-linearly and to handle feedback relationship.

Hence, this paper tries to examine the system dynamic model (SDM) in water security, especially in water quality and quantity in the coastal area. Thus, the research question is:

1. What is the subsystem related to coastal water security?

Methods

The scope of the study is reflected through a systematic literature review, which is a structured literature evaluation method which can aid in gaining information regarding study question. To identify relevant papers to address study question, a search was conducted on the "Google scholar," "SpringerLink," "Wiley," "Scinapse," and "PubMed" bibliographic database. To obtain a sample of papers, we used the following search strings: SDM OR system thinking OR system approach OR causal loop OR stock-flow OR feedback loop OR causal mapping AND water AND coastal.

For the first time, there are 12162 articles that match with the search string. Then, we selected those articles based on the titles, abstract, and keywords. We focused on the papers published in peer-reviewed journals from 2009 to 2019. Our search was conducted in November 2019 so that the papers published afterwards do not include. To exclude the irrelevant papers from the analysis, we exclude some papers based on exclusion and inclusion criteria (Tables 1 and 2). The inclusion criteria were based on the dimension of integrated water resources management (IWRM) [13]. All the selected papers that met the criteria below were excluded from analysis.

Table 1: Exclusion criteria in the systematic review

S. No	Criteria
1	Non-peer review journal, books, books chapter, master, and PhD thesis
2	Other language than English
3	Papers referring to dynamic system but not using the system dynamic method
4	Different subjects than the water security in the coastal area
5	Review article on related topics

Table 2: Inclusion criteria in the systematic review

The dimension of integrated water management (integrated water resources management)	Criteria
Water resources dimension	Coastal water (surface and groundwater)
Human dimension	Urban and rural setting
Spatial dimension	Coastal area
Temporal distribution	Varied (2009–2019)

Once the title and abstract of each paper were screened, the full version of the paper which potentially related to topics was downloaded. After assessing and extracting the details of each paper, while applying the exclusion criteria, a final sample of 12 papers was obtained for further analysis. Figure 1 presents a flowchart showing the process, we followed to obtain the final sample of papers.

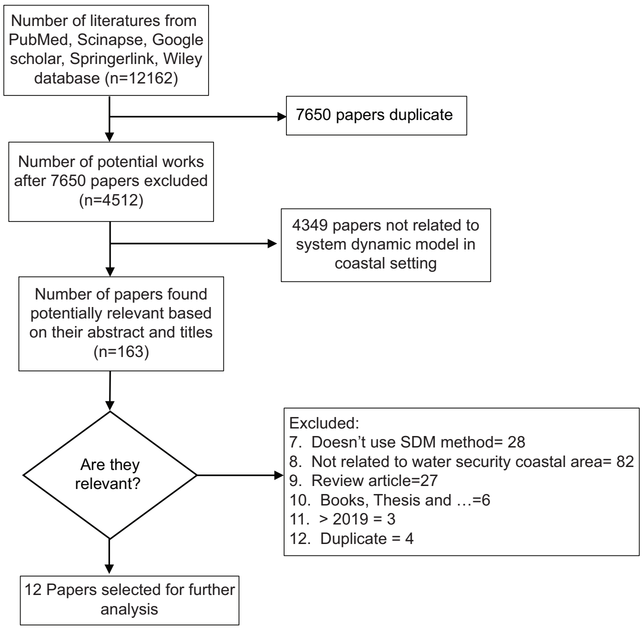

Figure 1: Flowchart of paper selection process

Results and Discussion

Data extraction

From 12 papers selected, we extracted information based on publication trends, geographical location, and dimension of IWRM (water resources setting, human dimension, spatial, and temporal dimension).

After assessing the papers in detail, the results show that selected papers, published in international journals and indexed in the bibliographic databases selected, use system dynamic methods in the field of coastal water security. Regarding the geographic location of coastal water security systems analyzed by the system dynamic approach, Asia countries have received the most attention about water security with six papers. It was followed by Australia, Europe, and America country with 3, 2, and 1, respectively. We found that there are only three papers in the period 2009–2014 and nine papers published in 2015–2019.

Dividing three topics about water security in the coastal area that includes water quantity related to water scarcity, water quality related to water pollution, and integrated water security related to both water quantity and water quality, only one paper examines integrated water security in the coastal area. The majority water-related problems facing in the coastal area are water-related quantity or water scarcity. Water scarcity is one of the most challenging problems in the world [33]. Rapid population growth is indicated as one of the factors [33], [34]. Moreover, climate change also harms water resources management, increasing the frequencies of extreme events such as floods and droughts, and increasing water demand for irrigation [33].

In this paper, we used integrated water resources (IWRM)'s dimension to analyze water security problem facing coastal area. Water security implies to ensure freshwater, coastal and related ecosystems are improved and protected, minimalize the risk of water-related hazards, promote sustainable development and political stability and also promote enough safe water for everyone. IWRM concept aims to manage the water resources in a comprehensive and holistic way. Savenije and Van der Zaag had divided IWRM into four dimensions:

1. The water resources or natural dimension, include all forms of occurrence of water including saltwater and fossil groundwater. It also divided into blue water and green water. Blue water is the water in lakes, rivers, and shallow aquifers, while green water is the water in the unsaturated zone of soil, which responsible for producing biomass. Moreover, in this paper, we conclude that there are two water resources in the coastal area, are surface water and groundwater. Based on the summary of the literature, developed countries such as Spain, Greece, and Australia are already using rain-independent water resource to support availability water source in the coastal area [12], [35], [36], [37], [38], [39], whereas developing countries still using rain-dependent water resources (i.e., groundwater and surface water) [6], [40], [41]. Table 3 shows that there are several water resources in the coastal area. Moreover, Table 4 showed that the majority of water resources explained in the prior research is surface water.
2. The water users, there are many different users of water and needs. The function of water includes economic production activities, maintaining dynamic equilibrium in natural processes, sustain life forms, contribution to culture, religion, and landscape. While water users include consumptive and non-consumptive users. We also divided the users based on the location setting; there are two types of users include urban and rural society. There are nine papers

Table 3: Coastal water resources [6], [12], [33], [34], [35], [36], [37], 38], [40], [42], [43]

Coastal water resources	Sources
Groundwater	Aquifer
Surface water	Runoff from rainfall, irrigation water, rivers, dam, estuarine water, stream, lakes, canals, reservoir, sea water
Rain-independent water	Desalinated water, recycled water, storm water recycled
Rain-dependent water	rivers, dam, estuarine water, stream, lakes, canals, reservoir, aquifer

Table 4: Summary of the studies that have used system dynamic model in coastal water security

No	Authors	Journal title	Purpose to use system dynamic model	Location	Water security topics	Integrated water resources management				Subsystem in system dynamic model	Scenario
						Water resources	Water users	Spatial scales	Temporal scales		
1	Sušnik *et al.* [40]	Integrated System Dynamics Modeling for water scarcity assessment: Case study of the Kairouan region	To reproduce credible behavior characteristics that pertains to the aquifer water volume.	Kairouan Region, Tunisia	Water quantity	groundwater	Urban society/ consumption	Local level	40 years (2010–2050)	Upper catchment area (Upper skhira), middle catchment area (mid-Merguellil catchment), El Haouareb reservoir, surface water input, coastal pumping, domestic, industrial and agricultural water demand	Baseline run: all parameter used is business as usual (no intervention), domestic demand: Changing domestic demand parameter (price, per capita demand, population), industrial demand: changing all parameter about industry (demand, price, investment), Agriculture demand: changing agricultural demand (price, demand elasticity, global food price, water's tariff, irrigation profile), coastal pumping : reducing pumping volume
2	Huanhuan *et al.* [6]	System dynamics modeling for sustainable water management of a coastal area in Shandong province, China	To study and analyze the future sustainable water management of this city	Longkou City, China	Integrated	Groundwater, surface water, irrigation return water	Urban society, consumption	District level	30 years (2000–2030)	Agricultural demand, industrial demand, domestic demand which include variables: the urbanization level, industrial/tertiary industrial GDP growth rate, industrial water used, irrigation quota, treatment of domestic wastewater, COD discharge)	Scenario 0 = business as usual by assuming that the development policies and system structure don't have a large adjustment in the forecasting period Scenario 1= economic development scenario (increasing GDP growth rate of industry and urbanization level) Scenario 2= Resources conservation scenario (reducing water quota for industrial sector and domestic COD discharge) Scenario 3= sustainable development scenario by emphasizing economic development and protection of water resources at the same time
3	Borgomeo *et al.* [41]	Avoiding the water-poverty trap: insights from a conceptual human-water dynamical model for coastal Bangladesh	To test the effect of improvements in the reliability, operation and maintenance of water infrastructure on agricultural incomes and assets	Ganges-Brahmaputra-Meghna Delta, Bangladesh	Water quantity	Surface water	Rural society, consumption	District level	40 years	Agriculture production, flood occurrence, soil salinity, water infrastructure reliability, operation and maintenance, income	Scenario 1= reducing water infrastructure reliability, operation and maintenance, scenario 2=increasing flood occurrence
4	Rivers *et al.* 2011 [35]	Estimating future scenarios for farm-watershed nutrient fluxes using dynamic simulation modeling	To provide a means to illustrate watershed P flux and of predicting future P loss scenario	Peel-Harvey watershed, South Western Australia	Water quality	Surface water	Rural society, consumption	Local level	200 years (1900–2100)	Watershed system include nutrient storage, assimilation and release from the major components of the watershed environment (soil, runoff, groundwater, stream sediment and estuarine water and sediment)	Nutrient loss from soil, nutrient loss from groundwater, nutrient loss from stream
5	Li *et al.*, 2019 [34]	Simulation and optimization of water supply and demand balance in Shenzhen: A system dynamics approach	To analyzed key factors affecting the annual water supply and demand ratio	Shenzen city, China	Water quantity	Surface water, groundwater,	Urban society, consumption	District level	30 years (2000–2030)	Water supply (surface water supply and groundwater supply), water demand (agriculture, industrial, domestic, urban ecological water, public water demand)	Scenario 1=The condition is the same as in the year of 2015 (six parameters are set the same as those of 2015) Scenario 2=WSDR reaches 1 in 2020 with assume six parameters are set minimum demand Scenario 3=WSDR reaches 1 in 2020 with assume six parameters are set on optimum values
6	Mavrommati *et al.* [36]	Operationalizing sustainability in urban coastal system: A system dynamic analysis	to quantify the effects of human activities of urban coastal cities on the ecological condition of the receiving waters	Inner Saronikos Gulf, Greece	Water quality	Surface water	Urban society, consumption	Local level	43 years (1987–2030)	Wastewater volume, pollutant load, ecological system	Scenario 1=Baseline scenario assumes that the exogeneous parameters of the model continue to reflect past behaviour Scenario 2=Combined sewer overflows (increasing construction and operation wastewater treatment plant) Scenario 3=Scenario assumes that there will be an increase of the per capita GDP and increase water prices Scenario 4=Increasing water demand scenario assumes increasing income elasticity

(*Contd...*)

Table 4: (*Continued*)

No	Authors	Journal title	Purpose to use system dynamic model	Location	Water security topics	Integrated water resources management				Subsystem in system dynamic model	Scenario
						Water resources	Water users	Spatial scales	Temporal scales		
7	Phan *et al* 2018 [43]	Assessment of the vulnerability of a coastal freshwater system to climatic and non-climatic changes: A system dynamic approach	To explore the vulnerability of the coastal freshwater system in Da Do Basin	Da Do Basin, Vietnam	Water quantity	Surface water	Urban society, consumption	Local level	57 years (1993–2050)	Fresh water supply water demand with assume include parameter of irrigation system, water level, salinity level, domestic, agricultural and industrial water use, population growth, upstream flow, and industrial production	Scenario 1=Baseline scenario are set all parameters the same as in 2014 Scenario 2=Increasing industrial water use Scenario 3=Reducing agricultural water use Scenario 4=Changing upstream flow Scenario 5=Increasing sea level
8	Prouty *et al*., 2018 [38]	Socio-technical strategies and behaviour to increase the adoption and sustainability of wastewater resource recovery system	To simulate the system level behavior (i.e., adoption and sustainability performance) over time	Coastal village of Placenzia, Belize	Water quantity	Surface water	Rural society, consumption	Local level	60 years	Marketing subsystem (advertising), social subsystem (stakeholder power, site demonstration, decided to adopt RR, economic viability, environmental viability, level sustainability, confirmed by sustaining RR system), technical subsystem (tank option, design scale, total working volume, operation and maintenance expenditures, hydraulic retention time, TSS performance, BOD performance)	Scenario 1=Doubling the advertising frequency Scenario 2=Increasing stakeholder power Scenario 3=Increasing site demonstration Scenario 4=Increasing tank size for RR system
9	Sahin *et al.* 2015 [37]	Water security through scarcity pricing and reverse osmosis: a dynamics approach	To investigate the water system in SEQ as well as conduct scenario analysis	South East Queensland Region	Water quantity	Surface water and groundwater	Urban society, consumption	Regional level	100 years	Population growth, water demand pattern, environmental pattern, rain-dependent water resources, rain independent water resources,	Business as usual (BAU-1)=This parameter is set the same as initial simulation BAUD-1: Business as usual simulation with desalination application BAUP-1: Business as usual simulation with changing TDP pricing BAUDP-1: Business as usual simulation with application od desalination technology and changing TDP pricing Restriction 1=Restriction water use and there's no change TDP pricing
10	Scarborough *et al.* 2015 [12]	Long term water supply planning in an Australian coastal city: Dams or desalination?	To explore the sensitivity of the model to key assumptions, particularly those regarding economic variables such as social discount rate, water supply variables such as water security index	South East Australia	Water quantity	Surface water and groundwater	Urban society, consumption	District level	100 years	Population, water supply, water demand, restriction, reserve capacity, water security index, desalination operation, dams operation	Scenario 0=Baseline scenario assumed that the future supply will rely on rain dependent supply and there's no new desalination capacity investment Scenario 1=Increasing population growth rate Scenario 2=Changing social discount rate Scenario 3=Changing scale of capital investment Scenario 4=Changing land availability
11	Pouso *et al.* 2019 [39]	The capacity of estuary restoration to enhance ecosystem services: system dynamic modeling to simulate recreational fishing benefits	To link the key socio-ecological elements that shape the recreational fishing activity in the Nebioi, to explore how future environmental management decision, unexpected changes and climate change effects could affect the activity	The Ibaizabal-Nerbioi and Kadagua, Spain	Water quality	Surface water	Urban society, recreational activity	Local level	19 years (2011–2030)	Ecological subsystem and social subsystem	Scenario 0=The social-ecological condition of estuary in 2011 (all variable were fixed to show a stable situation Scenario 1=Changing ecosystem component that support the recreational fishing (physicochemical and biological variables) Scenario 2=Changing social capital (space availability and fishers characteristics, satisfaction fisher)
12	Zare *et al.* 2019 [42]	Improved integrated water resource modeling by combining DPSIR and system dynamics conceptual modeling technique	To develop decision support system and learning tool for investigating the effects of different drivers (policy and environmental) on the water shortage, deforestation, land use changes, flooding, environmental degradation	Gorganroud-Gharesu Basin, North-Eastern Iran	Water quantity	Surface water and groundwater	Urban society, consumption	District level	40 years	population, economic activities, land use-flood, water resources and supply, environment	Scenario 1=The scenario simulates the future of the water resource if the assumptions about drivers and management policies remain unchanged Scenario 2=Increasing water supply scenario Scenario 3=Increasing in sedimentation scenario Scenario 4=Increasing sedimentation and water supply

TDP: Thermal design power, COD: Chemical oxygen demand, DDP: Gross domestic product.

evaluating water management in urban setting and three papers describing water management in rural setting. Various human activities will affect the water quality of the coastal ecosystem. When it comes to the urban system, the interaction between human activities and coastal system is more intensified due to increase population density and related to economic activities [36]. Therefore, subsystem population and economy are important parameters to the water security system. The function of water is not only for human consumption but also industrial, agriculture, aquaculture, ecological, and recreational needs [39], [40].

3. The spatial scales: There is a different level of water resources include the international level, the national level, the province or district level, and the local level. Parallel to these administrative levels are hydrological system boundaries such as river basins, sub-catchment, and watershed. Six papers describing system dynamic modeling were used in local water management. The others are describing water management in the district and regional level. There is a decision of water resources management belong at different levels, which means the concept of decision making at the lowest appropriate level needs to be guided in the development of IWRM [13]. The basin facing significant water-related issues (i.e., flood damage, sedimentation, and subsequent risks to water security and environmental degradation) [42].
4. Temporal scales and patterns: The temporal distribution of water resources is vital, and so is the distribution over time of demand. In water resources assessments, the total amount of water available strongly depends on the possibility to capture floods. The SDM can predict supply and demand for water resources in the coastal setting. The range of time prediction is diverse in some papers, such as for 19, 30, 40, 50, 60, 100, and 200 years period of time [6], [12], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43].

SDM

Models are widely used in the water sector [34], [44]. Models provide predictions and forecasts for planning and management purposes. The definition of the model is a simplification of reality that is, at once, imperfect and incomplete. The less inclusion of all possible information makes the model useful [44]. Using the SDM for water management process is based on the increase of awareness in IWRM. Savenije and Van der Zaag stated that the water management process needs to integrate all of the system. Regulating only one system may not achieve the desired results.

The application of IWRM needs multidisciplinary, multisectoral, and multi-stakeholder integration in planning, management, and decision-making around water. Therefore, system thinking is needed to examine the holistic part of system, interrelationship each part of the water system, and pattern of its behavior over time [44]. System thinking and SDM are closely related because both have aspects of dynamic behavior occurring within the system. The conclusion of system thinking is a description of system dynamics, while system dynamic used system thinking as a tool to known relation within part of the system [44]. Besides, both have the same concept, including causal loop, variable, feedback loop, and delay.

SDM is the methodology for understanding certain kinds of complex problem [45]. SDM has the advantage to handle high-degree of non-linear, high-level, and multi-variable problems [6], [33]. SDM is typically used when formal analytical models do not exist, but the simulation process by linking number or quantitative process can be done (i.e., developing a system structure) [40]. System dynamic modelling is originally proposed by Jay W Forrester in 1950s for bussiness process [46]. This method aims to achieve system thinking by computer-based models in solving a complex management problem. Since the environmental problem involves complex interactions, some SDM has been formulated for environmental management and ecosystem assessment [40], [47]. SDM build aims to develop a model that closely mimics the system under investigation to the level of detail required. Moreover, SDM may be a useful tool for integrated water system modeling [6], [40].

To develop an SDM, there are several component systems include interlinked compartments (Stocks), directed links (flows), and influences (converters) [46]. Stocks can be thought of as storing a quantity of material such as money in the bank, the population of humans, and water in a reservoir. The value of stock is related to inflow/outflow of variable system to stock. If the inflows and outflows to/from stock are equal to zero, then the value of a stock will remain constant. Flows indicated movement of material into/from stocks (e.g., cash deposits or withdrawals, birth or death, water supply, and demand), whereas converters act to influence the rate of flows (e.g., birth rate or death rate) [40]. Lorenz and Jost reported that there are several characteristics of system dynamic (Table 5). Furthermore in the table 4. there are several scenario that is developed by using SDM.

Table 5: Characteristic of system dynamic [48]

Characteristic item	System dynamic
Perspective	Holistic, emphasis on dynamic complexity
Resolution of models	Homogenized entities, continuous policy pressures, and emergent behavior
Data sources	Broadly drawn
Problem studied	Strategic
Model elements	Physical, tangible, judgmental, and information link
Human agents represented in models as	Boundedly rational policy implementers
Clients find the model	Transparent/fuzzy glass box, nevertheless compelling
Model output	Understanding of structural source of behavior modes, location of key performance indicators, and effective policy levers

There are three steps of using SDM (Figure 2). At the first step, the researcher needs to clarify what is the water-related problem which wants to be solved. This process is related to choosing subsystem and parameters which input to the system. Then, the major equations and parameter process methods were described. The model was tested and the used for forecasting variables. Furthermore, the sensitivity analysis, parameters having a significant impact on problem-solving were selected and used in scenario analysis to develop regulation relating to water security. As the analysis method, system dynamic also has advantages and disadvantages (Table 6).

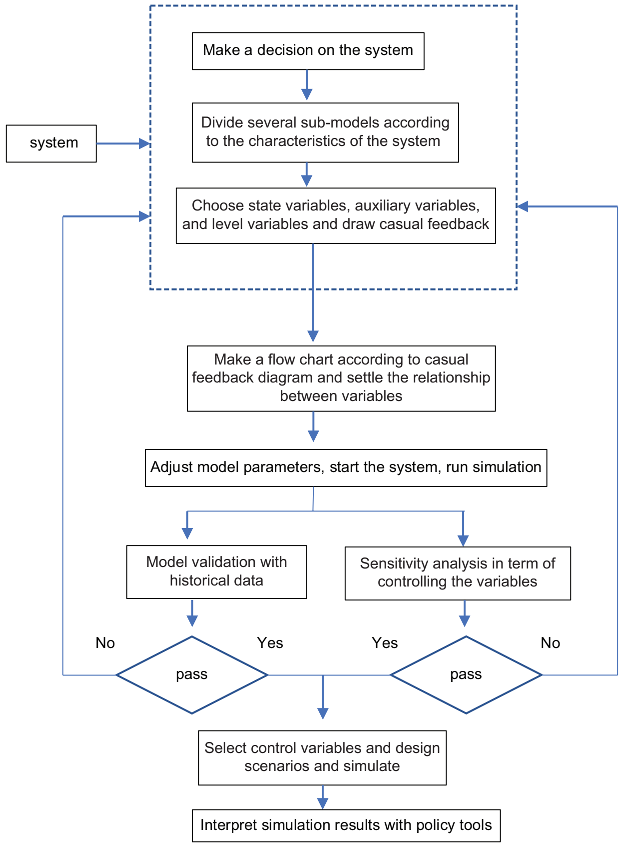

Figure 2: Research using system dynamic model framework [34]

Table 6: Advantages and disadvantages using system dynamic model

Advantages	Disadvantages
Involves complex interactions and handle many interdependent subsystem	Needs experts to interpretation of simulations
It is not only used for natural and anthropogenic system at variety system, but it can be effectively used to further local stakeholder engagement and knowledge	Difficulty of modeling iterative procedures within single model time step
Needs mathematical formula or quantitative models	Spatial modeling is not strictly possible
Needs third-party software to analyze such as Vensim or Stella	
Describe causal relationship between subsystem	
Flexibility of accepting any kind of variables/ parameter	
Using sensitivity testing and uncertainty analysis can be quickly and efficiently undertaken without the changes to model structure	

Sources: Huanhuan *et al.*, [6], Sušnik *et al.* [40].

Subsystem related to coastal water security

In this paper, we divided the coastal water security problem into two major problems: Water quantity problem and water quality problem. Water quantity problems relating to water scarcity have imbalance water supply and demand problem, whereas water quality relating to feasibility of water for human and ecological needs. The resume of subsystem related coastal water security represents in Figure 3 and Tables 4 and 7.

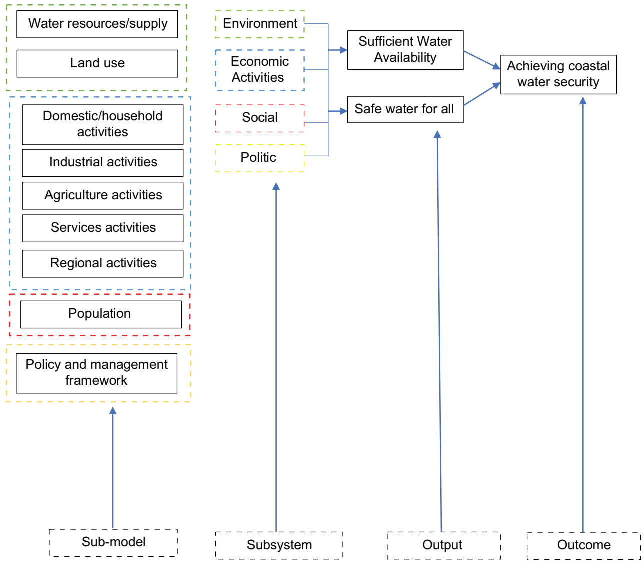

Figure 3: Subsystems in coastal water security

This paper examines that four subsystems or components that will affect to coastal water security include

1. Environment

This subsystem contains water resources and land use sub-model (Table 6). Subsystem environment is related to water system supply and demand, include all factors which are influence water availability. There are three types of coastal water resources include surface water, groundwater, and recycled water (e.g., desalination and wastewater treatment plant). Both surface water and groundwater strongly influenced by climate factors (e.g., evaporation, flood occurrence, precipitation, temperature, and sea level) [33], [40], [41].

The water surface volume is influenced by climate, area catchment of rainfall, volume water entering stream (runoff), volume water transferred out from main surface water source, domestic waste water rate, annual water deficit, water infrastructure, upstream flow, diverted water from outside surface water, flood or stormwater, sea level, and sluice gate system. The amount of water from surface water to aquifer influenced by rainfall frequency in surface land, evaporation coefficient, fraction of rainfall, total volume stored in aquifer, annual water deficit, and area catchment of rainfall [40]. Precipitation and temperature affect landscape water demand directly [33]. Climate change will influence the processes of landscape water evaporation and irrigation, and ultimately affects the total water demand [33], [41]. Study by Wei *et al.* (2016) used climate change factors to calculate urban landscape water demand.

The amount of water in water resources is also influenced by water conservation measures include

Table 7: Subsystem relating to coastal water security

Subsystem	Sub-model	Stock	Key variable	Source
Water-related quantity problem				
Environment	Water resource	Surface water resource/supply capacity	Climate	[40]
			Rainfall	
			Evaporation coefficient	
			Area of catchment	
			volume of water entering and out surface water system (runoff)	
			Domestic waste water treatment rate	
			Water deficit	[6]
			Water infrastructure reliability, operation and maintenance	[41]
			Water infrastructure damage	
			Water diverted from outside study area	[34]
			Water storage	[34], [37],
			Upstream flow	[43]
			Sluice gate inflow system	
			Sluice gate opening schedule	
			The fraction of land area	[41]
			The floodwater retreat	
			Sea level	[43]
			Tide level	
		Groundwater supply capacity	Climate	[40]
			Rainfall	
			Evaporation coefficient	
			Annual volume of water entering aquifer	
			Total volume stored in aquifer	
			Annual water deficit in aquifer	
			Area of catchment	
		Alternative water supply (wastewater treatment plant, desalination) capacity	Domestic wastewater discharge	
			Domestic wastewater reuse	
			Domestic COD discharge per capita	[40]
			Industrial COD discharge per industrial GDP	
			Desalination capacity	[12], [37]
			Size of desalination	
			Size of dam	
			Desalination capital cost	
			Dam capital and operational cost	
			Desalination cost	
			Coastal pumping	[40]
		Water conservation measures	Water saving per capita	[33]
			Changing water conservation	
			Water restriction	[37]
	Land use	Ecosystem area	Vegetation area	[42]
			Urban and service area	
			Industrial area	
			Agricultural area	
			Bare area	
Economic	Services activities	Service employment	Service employment	[42]
			Service GDP	
			Service water consumption	
			Service water need	
			Desired water need	
	Industry activities	Industry employment	Industry employment	[42]
			Industry GDP	
			Industry water consumption	
			Industry water need	
			Desired industry area	
			Proportion of revenue invested for water savings	[40]
			Price elasticity of demand	
			Water tariff	
			Industrial production	[34]
	Agriculture activities	Agriculture employment	Agriculture employment	[42]
			Agriculture GDP	
			Agriculture water consumption	
			Agriculture water need	
			Desired agricultural area	
			Crop irrigation quota	[6]
			Yield agriculture	[41]
			Agriculture production	[41]
			Agricultural income	
			Soil salinity	
			Agricultural income	
			Water saving efficiency	[40]
			Water price	
			Global food price	
	Domestic/household activities	Population	Total population	[42]
			Migration	
			Rate of growth population	
			Domestic water demand per capita	[6], [33],
			Price elasticity of demand	[40]
			Water tariff	
			Water saving behavior	
			Annual water demand	
	Regional activities	Regional water utility	GDP per capital	[42]
			Total environment	
			Regional utility	
Social	Population	Total population	Birth rate	[42]
			Total amount of births	
			Death rate	
			Total amount of deaths	
			Net migration	

(*Contd...*)

Table 7: (*Continued*)

Subsystem	Sub-model	Stock	Key variable	Source
Water-related quality problem				
Environment	Water resource	Water pollution	Nutrient P loss to watershed (runoff)	[35]
			Soil P loss	
			Total nitrogen	
			Turbidity	
			Pollutant loads (BOD and TSS)	
			Salinity	[43]
			Heavy metals (Cd and Zn)	[39]
			Oxygen saturation	
			Total water debit	[36]
			Domestic COD discharge per capita	[6]
			Industrial COD discharge per industrial GDP	
		Ecological Status	Ecological status	[36]
			Ecological evaluation index	
		Wastewater capacity	Wastewater flow	[36]
			Treatment efficiency	
			Resident water flow	
			Non-residential flow	
			Urban runoff	
			Water demand per capita	
			Wastewater capacity	
			Combined sewer overflows	
			Water price	
			Treatment cost per capita and activity	
			Non-residential wastewater debit	
			Residential wastewater debit	
			Domestic waste water treatment rate	[40]
Politic	Policy and management framework	Policy	Ecological sustainable development policy	[36]
Social	Human activities	Population	Total population	[36]
			Births	
			Deaths	
			Net migration	

water saving per capita, water restriction, and willingness of water conservation in society. The water conservation is hypothesized that residents' water demand increases with growing material needs, and decreases with growing water conservation willingness [33]. Because of consumers' choice or willingness has significant impact on the environment. Land use sub-model representing total of urban and services, industrial, agricultural, and bare land area. This component affects socio-economic subsystem [42].

In relating to water quality, water resources sub-model includes water pollution, ecological status, and wastewater capacity. The water pollution will be influenced by total amount of nutrient (nitrogen and phosphorus), heavy metals (Zn and Cd), water resources debit (rainfall, surface water debit, and groundwater debit), and wastewater discharge debit. There are several parameters to determine water quality include turbidity, biochemical oxygen demand, dissolved oxygen DO, TSS, nutrient loss to watershed, and ecological evaluation index. From the literature review, information about the mechanism of pollutant enters the environment and role of water scarcity on coastal water pollution is still limited. Due to us only have three papers about coastal water quality and one paper about integrated coastal water management from 2009 to 2019.

2. Subsystem economic

Subsystems economic include services activities, industry activities, agriculture activities, and domestic/household activities sub-model. Economic sub-model represents water demand in four different sectors. All of economic sub-model is influence by employment, gross domestic product (GDP), water consumption, production from activities, water need, water desired, water tariff, and proportion of water saving. For agriculture sector, water demand is also influenced by soil salinity [41]. From the literature, the literature about the relationship between coastal water management and marine-aquaculture activities in coastal area is still limited, whereas the marine-aquaculture sector is one of the important economic activities on the coastal area [49], [50]. The utility of blue water (i.e., surface and groundwater) in aquaculture also makes a significant contribution to global fish production [50]. The rapid development of aquaculture is associated with ecological concern including habitat destruction, water pollution (nutrient and chemical substances), eutrophication, biotic depletion, ecological effects, and disease outbreaks [49]. Only one paper examines about improving water quality and fishing satisfaction in coastal area [39]. The ecological restoration is positively impact to fish abundance and richness thus increased fishers satisfaction [39].

The GDP is very important factor influencing water management due to economic growth directly relates to water consumption and environmental pressure [51]. Furthermore, GDP is one of the main driving forces of commercial water demand [33]. For example, a survey in Bangladesh shows that there is a correlation between water dynamic and poverty. A water-related issue that impairs livelihoods in the coastal area includes soil salinity, flooding, deteriorating embankments, and drainage congestion due to lack of system operation and maintenance [41].

The flooding event (river floods, tidal floods, and storm surge floods due to tropical cyclones) in Bangladesh causing abrupt losses in agricultural yields and income [41]. Moreover, soil salinity, flooding, and decaying water infrastructure will impair agricultural production. These agricultural production declining leads to declining incomes and assets. Domestic assets also suffer periodic shock due to floods; it called the water-poverty trap [41]. Besides, there is a relation between the ability of investments in water-related infrastructure to increase the factor productivity of water as an input in different sectors of economy diminishes, while the presence of water-related hazards has a detrimental effect on economic growth. Shifting water-related investment from increasing economic production to mitigating hazard-related losses/water security may increase human well-being directly and increases economic growth indirectly (through reduced water-related disease and increased labor productivity) [5].

3. Subsystem social

Subsystem social consists of population growth and human activities relating waste discharge. The population growth and human activities are involved in ecological sustainable development concept as key factors [36], [52]. There is interaction between population, workforce population, and GDP variables [42]. Furthermore, the economic welfare, employment, flood hazard, and vegetation area will affect this subsystem [42]. The affecting factors including socioeconomic and population growth can well depict system behavior and predict population and GDP growth. In many research about environment relating system dynamic, population growth is always as input of system which related to another subsystem [51]. In water management, population growth will affect both water demand and water pollution [12], [33], [37], [40], [41], [42], [43], [51]. The population is mainly influenced by the regional birth rate, mortality rate, and population migration [36], [42], [51], [52], [53], [54]. Subsystem population will affect the supply and demand for water. Furthermore, human activities will affect ecosystem health with pollutant discharge to the water system. Moreover, urbanization is characterized by rapid economic and population growth in cities, accompanied by a rapid increase in water demand.

4. Subsystem politic

This subsystem contains only one sub-model is policy and management framework. Study conducted by Mavrommati, Bithas and Panayiotidis, (2013) using ecologically sustainable development (ESD) to develop the model. In those studies, policy for the aquatic ecosystem is included in ESD concept. To achieve sustainable science between human and natural system requires the integration of knowledge of social and natural science into a common framework of analysis and thinking [36]. The water framework directive and the clean water act are adopted to determine knowledge from natural and social science. Environmental policies defined ecological targets and employ various policy instruments to regulate socio-economic activities [36]. Furthermore, policy incorporated into the study is an endogenous parameter linked to sustainability target such as GES. Besides water pollutant entering and influencing coastal water security aspect are still limited. In relating to sustainable development, there are no articles which examined human health risk relating to water security.

The functions of subsystem determination are to consider variables which are incorporated in a SDM. After the variables selected, the simulation needs to be done. During the simulation, only the variables under investigation were changed to observe the impact on model response. The others were as in the standard run. In respect to coastal water security, the simulation process aims to identify which parameters in which sectors have the greatest impact on coastal water security and, therefore, may act as a future guide or focus for policy decision.

Conclusion

In the previous sections, the subsystem of coastal water security was explored. This study helped us to gain a better description of the subsystem of coastal water security incorporating into a SDM. There are 12 papers selected and reviewed. All the selected papers showed the relevance of the SDM in coastal water security. The implementation of SDM is suitable for water management in the coastal area due to the complexity and dynamic characteristic of the coastal area. There are many factors influencing water availability and water quality in the coastal area. The aim of the system dynamics is to simulate the structure of a various complex system and to analyze the internal relation of the system. These factors categorized into four main subsystems include the environment, economic, social, and politic. Subsystem environment consists of several sub-models include water resources and land use. Subsystem economic is related to economic activity influencing water demand and wastewater discharge. There are four main sub-model in the economic subsystem include services, domestic, industry, and agriculture activities. Subsystem social is related to population growth and human activities. The last subsystem is politic which only has one sub-model is policy and management framework. The subsystem determination is important to develop SDM due to it uses in simulation for future policy relating water security making. Recommendation for further research is (1) adding aspect aquaculture activities as one of the factors influencing coastal water security, (2) adding aspect about the mechanism of pollutant entering to a coastal water system, and (3) the relationship between water security and human health risk.

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