Journal of Water and Climate

Critical Review of salinity intrusion in rivers and estuaries

--Manuscript Draft--

Manuscript Number:	JWC-D-16-00134R1
Full Title:	Critical Review of salinity intrusion in rivers and estuaries
Article Type:	Review
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Critical Review of salinity intrusion in rivers and estuaries

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Abstract

There is scientific evidence of accelerated sea level rise and saline intrusion. Some impacts, such as stratification and estuarine circulation are subtle; others are dramatic including shifts in salt-sensitive habitats and limited water availability of suitable quality for industrial and municipal uses. These results have become a remarkable reality resulting in a set of integrated surface water organisation issues. Tremendous population increases overwhelming many coastal areas have expanded the problem. These challenges have been studied from many perspectives using various objectives and methodologies, and then arriving at different findings. However, all research assured that significant rises in sea level have influenced estuaries and tidally affected rivers, and these observations are expected to become rapidly worse in the future. This study introduces categorises, critically investigates, and synthesises the most related studies regarding accelerated sea level rise and challenges of the development associated with the resources of surface water in estuaries and tidally-affected rivers. This critical review reveals that there is a need for research that focuses on the development of sustainable surface water resources.

Keywords: Climate change; Coastal resources management; Estuary; River discharge; Tidal analysis; Water Resources Management.

Introduction

Background, aim, and overview

Amongst all recent universal, ecological and public alterations, climate variability, as estimated by many climate models (IPCC 2007), will have severe influences on coastal areas. There is an extensive variety of effects containing rising sea level, rain patterns, floods, and drought occurrences. These impacts may have important influence on natural resources, particularly water resources (ground or surface). This is mainly challenging for estuaries, where both natural and socio-economic resources of great importance available and are developing quickly.

Estuaries, in the traditional sense, are transition zones between upland rivers and coastal waters, and are critical nursery regions providing grounds for a considerable number of marine animals (Zhang et al. 2012; Chen et al. 2013; Jacob et al.2013; Chen et al. 2014; Liu & Liu 2014; Xu et al. 2015). The leading environmental factors impacting on the survival and distribution of organisms in estuaries are salinity distribution and intrusion (Attrill 2002; Chen et al. 2009; Khadim et al. 2013; Chua & Xu 2014; Garcia et al. 2010; Hong & Shen 2012; Renaud et al. 2015). The structure of salinity patterns in estuaries results from the interplay between estuarine themorphology and topography, tidal elevation at the estuary mouth, saline water variation between ocean and freshwater discharge. Therefore, these factor interactions determine the estuarine mixing mechanisms and the saline water movement process (Shaha et al. 2011; Xu et al. 2015). Saline intrusion may lead to estuarine water quality decline so that the corresponding water becomes inadequate for specific purposes including drinking water, agricultural, and industrial uses (Renaud et al. 2015). Accordingly, the simulation of saline water distribution along an estuarine system is often seen as the prime concern of decision-makers in estuarine systems and coastal areas (Bhuiyan & Dutta 2012; Hong & Shen 2012; Rice et al. 2012; Liu & Liu 2014).

Many water resources researchers are interested in salinity intrusion in estuaries, and they undertook it from many perspectives, concentrating on either groundwater or surface. Various tools have been applied to characterise, categorise, and analyse salinity distribution in estuaries. Most of the research confirmed that sea level rise is a substantial problem that should be discussed with high importance. Key references related to the link between salinity intrusion and sea level rise are summarised in Table 1.

Table 1. References related to salinity intrusion and sea level rise (SLR)

Reference	Location	Finding
Kurup et al. (1998)	Swan River estuary, Australia	The freshwater river inflow is the most critical process impacting on the salt wedge site.
Liu et al. (2004)	Tanshui river system, Taiwan	The average annual salinity was 8.5 parts per thousand (ppt) and 12.8 ppt before and after the construction of the reservoir in this order.
Liu (2005)	Keelung River, Taiwan	The boundaries of saline intrusion before regulation of the channel were further upstream of the river compared to after channel regulation.
Liu et al. (2007)	Danshuei River estuarine, Taiwan	The two-layered circulation within the estuary prevails most often at the estuary mouth.
Xue et al. (2009)	Changjiang River, China	The salt-water movement resulted from a complex non-linear interaction process in relation to freshwater flow upstream, tidal currents, water mixing, wind impact, and saltwater distribution.
Jeong et al. (2010)	Modaomen Estuary, China	During neap tides, the estuary gains salt, whilst during spring tides, it loses salt.
Cai et al. (2012)	Modaomen Estuary, China	The estuary would be increasingly exposed to salt intrusion and to flooding from storm surges as a result of further deepening, which facilitates the penetration of storm surges into the system.
Bhuiyan and Dutta (2012)	Goral river network, Bangladesh	A 59-cm rise in sea level increases the salinity by 0.9 ppt at a distance of 80 km upstream of the river mouth.
Rice et al. (2012)	Chesapeake Bay, USA	With 50 cm and 100 cm sea level rises, the maximum salinity increases would be 2 and 4 ppt, respectively.
Chen et al. (2013)	Wu River estuary, Taiwan	More tidal energy will spread into the estuary after weir construction.
Mendes et al. (2013)	Douro estuary, Portugal	The amplitude of the principal lunar semi-diurnal tide constituent increased for almost the entire estuarine area
Liu and Liu (2014)	Wu River estuary, Taiwan	The overall flushing time extracted from the system for high flow without sea level rise is lower in comparison to the sea level rise.
Chen et al. (2014)	Tamsui River estuarine, Taiwan	The maximum increment of depth-averaged and tidal-averaged salinity would be 1.1, 2.4 and 3.0 psu in this order for corresponding sea level rises of 0.34, 1.05 and 1.40 m at the middle region of the estuary under the average discharge scenario.
Kuang et al. (2014)	Yangtze River Estuary	The ebb flow split ratio increases up to almost 5% under a 2-m sea level rise scenario.
Liu and Liu (2014)	Wu River estuary, Taiwan	The tidal expedition further upstream increases by 500 and 900 m under the Q_{10} and Q_{90} discharge scenarios, respectively.
Xiao et al. (2014)	Marks River Estuary, USA	A 0.85-m sea level rise caused a substantial increase in salinity near the Wakulla River with an increase of 9.2 ppt for the surface and 12.7 ppt for the bottom salinity.
Chua and Xu (2014)	No specific location (i.e.: idealised estuary model)	A sea level rise causes a strong longitudinal saline water gradient, higher longitudinal dispersion coefficients and increased saline water movement.

This research tries to specify the key outcomes of most current studies regarding sea level rise and development challenges that estuaries and tidally affected rivers face with especial attention to surface water. This critical review should serve as the bases for specifying further research requirements. Accordingly, the current study is arranged into various sections. In the second one, recent articles concerned with the temporal and spatial variations of saline water upstream movement in the estuarine systems and the underlying driving mechanisms are discussed. Details associated with the responses of saltwater intrusion to streamflow and tidal mixing are included. The third section assessed the most important articles that investigate the impact of human interventions in coastal areas, such as channel regulation and dredging, weir construction, seafloor bathymetry alteration, and freshwater diversion on the inland migration of saline water. The fourth section introduces the various hydrodynamic and solute transport numerical models predicting the impacts of sea level rise on saline intrusion. Section five discussed future research directions that would enhance understanding of hazards linked to saline intrusion as well as help basin managers and decision-makers to establish adaptive strategies.

Although this paper will investigate a sufficient number of literature sources, it looks to be ultimately difficult to contain all publications in a single review paper. It is, therefore, likely that some features of the theme have either been unnoticed or only concisely discussed. Some of the river and estuary research saline water intrusion aspects have been deliberately considered only slightly. Therefore, they merit a more comprehensive specialised review. It is anticipated that these gaps could be covered by following timely contributions. There is certainly target for further discussions related to salinity intrusion research, probably in the broader context of future improvement of total estuarine and coastal science.

Factors affecting the saline intrusion

Freshwater flow and tidal mixing

One requires a good understanding of river discharges and water movement within an estuary to accurately predict the hydraulic transport of materials (e.g., pollutants and sediment) within streams to an estuary and then into the ocean. The two hydrodynamic characteristics of tidal rivers are incorporating fluvial and bi-directional flow. The former includes seasonal and transient variations of freshwater discharge, while the latter is dominated by tide, and complicated by salt-freshwater inter-action as well as meteorological events (Liu et al. 2001).

The volume of river flow is the predominant factor affecting estuarine saline intrusion and plays a key role in depressing inland saltwater, particularly when river flow is sufficiently high to fill the entire tidal prism completely through the phase of rising tide (Liu et al. 2001; Liu et al. 2007; Graas & Savenije 2008; Gong & Shen 2011; Cai et al. 2012). A growing number of studies have been conducted to investigate the temporal and spatial differences of saline water movement in the estuarine system and associated driving mechanisms. Among them are Kurup et al. (1998), Gibson & Najjar (2000), Liu et al. (2001), Liu (2006), Liu et al. (2007), Xue et al. (2009), Becker et al. (2010) and Trieu & Phong (2015). In their studies, they used different analytical and hydrodynamic and solute transport models for an estuary with tributaries, in addition to the main stream to investigate the change in estuarine circulation and salinity distribution under different hydrological situations. They proposed that salt intrusion increase within the estuary can be linked to various factors, such as upstream river discharge decrease, the river mouth tidal amplitude increase, and dredging activities.

Their simulation results demonstrated that salt-water movement resulted from a complex non-linear interaction process in relation to freshwater flow upstream, tidal currents, water mixing, wind impact, and saltwater distribution. Additionally, they demonstrated that river flow is the most important natural process impacting on the salt wedge site and plays a major role in preventing inland movement of saline water, in particular, when the flow of the tidally affected river is high. For example, they noticed that the reduction of the river flow to the flow that is equal to or exceeding 75% of time (Q_{75}) increases the extent of saline water intrusion. Moreover, they suggested that more turbulent mixing, which in turn increases the salt intrusion, lowers vertical stratification, and less residual circulation result from the spring tide.

The estuarine system residence time can increase with the change in river flow during a scenario of rising sea level. This scenario reveals not only an alteration in saline water movement, but also a rise in the time of residence. A rise in sea level is likely to change the river estuary location, thereby leading to a considerable alteration in both fish environment and breeding ground location. Fishes usually breed in estuarine systems and develop further in saline waters. It follows that a rise in sea level would shift this boundary upstream, altering the environment of fishing populations. The rises in residence time as a result of sea level rise are likely to extend the movement of dissolved materials, which would result in the decline of the corresponding water quality.

Water transfer projects can effectively mitigate saline water movement. Saline water intrusion and river flow discharge can be predicted faster and by a simpler method through using two optimal regression equations, which provide a policy-making basis allowing for a fast response to deploy corresponding preventive measures to minimise risks in case when the saline water intrusion occurs.

Gong & Shen (2011) improved a modelling system based on nested grids to simulate the saline water transport processes and the corresponding saline water intrusion response to alterations in streamflow and tidal mixing in the Modaomen Estuary, China. They showed that during neap tides, the estuary gains salt, whilst during spring tides, it loses salt. The researchers also confirmed that the streamflow pulse overturns the corresponding saline intrusion greatly.

All in all, the responses of saline water intrusion to streamflow and corresponding tidal mixing have been researched in detail by Turrell et al. (1996), Uncles & Stephens (1996), Chen (2004), Prandle (2004), Sierra et al. (2004), Brockway et al. (2006), Huang (2007), and others. These studies confirm that the magnitude of freshwater flow is the predominated factor impacting estuarine saline intrusiony and plays a key role in reducing inland saltwater, which can lead to contamination of drinking water sources and other consequences.

Manmade activities and interventions

Many studies showed that there are various other parameters that might affect the movement of saline water in coastal areas in addition to river discharge and tidal level variation (Bobba 2002) such as anthropogenic interventions (e.g., river regulation). For example, changes in seafloor bathymetry play a considerable role in saline water movement. Therefore, to investigate the hydrodynamic characteristics and salinity intrusion in the estuary in response of the bathymetry alteration, Liu et al. (2004) mimiced salinity distributions in the Tanshui river, Taiwan, under various bathymetric configurations and for three flow scenarios (mean flow (Q_m), the flow that is equal to or exceeding 50% of time (Q_{50}) and the flow that is equal to or exceeding

75% of time (Q_{75})) at the upstream boundaries of three system tributaries both before and after the construction of a reservoir by applying a vertical, laterally integrated, two-dimensional hydrodynamic and saltwater intrusion model. Their results showed that both changes have led to further intrusion of tidal flow and upstream salt-water presence. Furthermore, the salinity increased throughout the year and the average annual salinity was 8.5 parts per thousand (ppt) and 12.8 ppt before and after the construction of the reservoir in this order. Then, Liu (2005) utilised the same model to assess the change in tidal ranges, saltwater intrusion and residual circulation that result from channel regulation in the Keelung River, Northern Taiwan. The researcher detected that the boundaries of saline intrusion before the channel regulation were further river upstream than after channel regulation, because of the impact of a deeper and wider channel as well as the fundamental decline in saline water, which was observed along the estuary after the channel regulation.

Sanders & Piasecki (2002) formulated and subsequently applied an optimisation problem by a quasi-Newton method, which uses a Broyden-Fletcher-Goldfarb-Shanno update to assess the gradient of the objective function with respect to the parameter vector (Shanno & Phua 1980). They discovered that salinity sensitivity levels to freshwater diversion from estuaries, for municipal and agricultural purposes, have both intra-tidal and inter-tidal variability. Diversions at any period and at any point throughout an estuary have either a long-term or a rapid impact on the salinity distribution.

Chen et al. (2013) established and applied a three-dimensional hydrodynamic water quality model to predict the possible influences of the Dadu Weir located at the Wu River estuary, Taiwan, in terms of saltwater intrusion and water quality changes under low flows. The model applications revealed that more tidal energy will spread into the estuary after the weir construction as a result of reduced freshwater discharges. Thus, the salinity will subsequently increase.

The prevention of salt-water intrusion is fundamental to estuarine system management. The storage system directly affects the downstream river discharge, which influences salt water intrusion intensity and disturbs freshwater intake at, for example, reservoirs located within the estuary boundaries. The reservoirs are normally operated on a seasonal scale. Accordingly, it is important to investigate the effect of seasonal regulation of streamflow by reservoirs on salt-water intrusion. Thus, a quantity assessment of this critical issue is important for the active management of water resources within the estuary boundaries.

Saline water movement enhancement and advancement has a negative influence on the preservation of freshwaters. Saline intrusion becomes minimal in the estuary at a time when water is released from river storage systems during dry periods.

Eventually, Li et al. (2014) evaluated the future availability of freshwater in the Changjiang example estuary by undertaking a hydrological investigation based on the examination of the available discharge, salinity, water diversion projects, and sea level rise. They extrapolated salinity events into the future at intervals of ten years until the year 2040. The results explained that the scarcity of estuarine freshwater scenario is complicated by both the salinity intrusion through the North branch and the diversion of flow from the Changjiang estuary downstream of the Datong gauging station.

Human interventions in the form of tidal river management are motivated by addressing saline water intrusion challenges in coastal regions. For example, Khadim et al. (2013) evaluated the benefits achieved due to the implementation of integrated water resources management strategies in some coastal regions, and assessed some technical aspects involving a new tidal river management concept.

Climate change

Overview

One of the most serious environmental issues facing the world is climate change. It is widely accepted that global warming has the potential to affect many humans dramatically and predominantly adversely as a consequence of both natural and anthropogenic changes to temperature, precipitation, sea level, air quality, and other climatic conditions (Mendes et al. 2013; Chen et al. 2014; Liu & Liu2014; Scholz 2014).

Sea level rises result from three main causes: ocean thermal expansion as well as mountain glaciers and ice cap melting pose a particularly disastrous threat, because they have long-term impacts on coastal areas, such as increase in coastal erosion and sea water intrusion (IPCC 2007; Woodworth et al. 2009). The fifth evaluation report of the inter-governmental panel on climate variation explained that the average rate of global mean sea level increased by 1.7 mm per year between 1901 and 2010, and it is very likely that this rise will continue beyond the 21st century (IPCC 2013). For the period between 2081 and 2100, their latest report expects a future rise in global sea level between 0.45 m and 0.82 m for the most pessimistic scenarios (IPCC 2014).

A rise in sea level can lead to migration of saline water upstream in both estuaries and rivers due to many factors, such as density difference, tidal range, freshwater flow, increase of the cross sectional area, and mixing process. Such a harmful movement may deteriorate estuarine water quality, so that its water will be unsuitable for drinking, agricultural and industrial purposes (Farber et al. 2005; Pathikonda et al. 2010; Bhuiyan

& Dutta 2012; Rice et al. 2012 Chen et al. 2013; Liu & Liu 2014). Furthermore, this could cause alterations in salt-sensitive habitats and negatively impact on the fauna and flora development. Thus, the saline water distribution alongside an estuary is a prime concern for the water management (Bhuiyan & Dutta 2012; Hong & Shen 2012; Rice et al. 2012; Khadim et al. 2013; Liu & Liu 2014).

Generally, the sea level rise impact on coastal areas water management can be divided into three parts: coastal zone and the hinterland, estuaries and rivers, and coastal groundwater flow regimes. Figure 1 reveals relevant aspects that affect the coastal areas due to sea level rises.

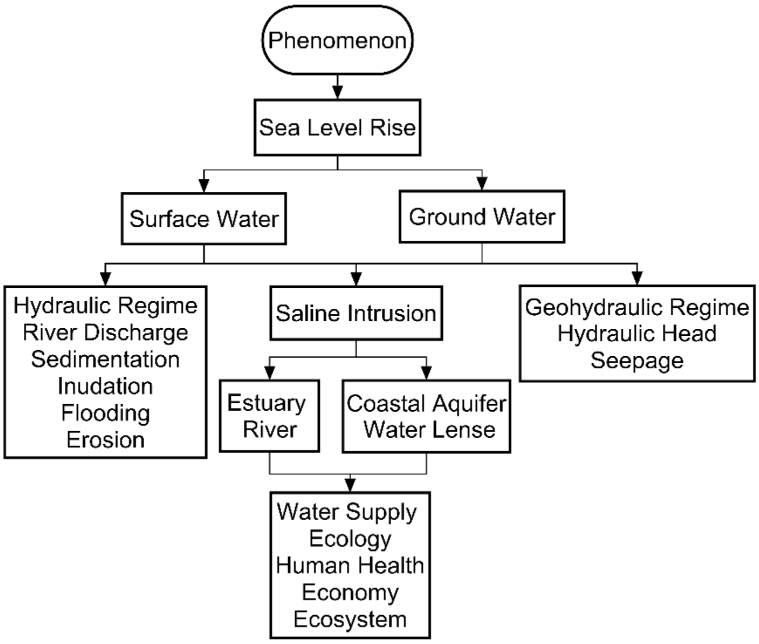

Fig. 1. Relevant aspects that affect coastal areas due to sea level rise

A rise in mean sea level has many consequences in coastal areas including a higher risk of low-lying coastal area flooding, sandy beach erosion, saline water intrusion and the loss of wetlands (Kirwan et al. 2008; Poulter & Halpin 2008; Gesch 2009). Such impacts will lead to geomorphological, ecological, and socio-economic effects in coastal areas (Michael 2007).

Understanding sea level rise implications on estuaries has attracted many researchers worldwide. The impact on estuaries and tidally affected rivers is of key interest.

Climate change and sea level rise

One of the significant impacts of climate change is sea level rise. The fifth assessment report of the IPCC (2013) explained that the average amount of global mean sea level increase was 1.7 mm per annum between 1901 and 2010 (Fig. 2). Patterns and trends of sea level rise can be investigated either through linear regression for long-term data obtained from tidal gauges and satellite altimetry or by considering certain scenarios set by the IPCC as illustrated in Fig. 3.

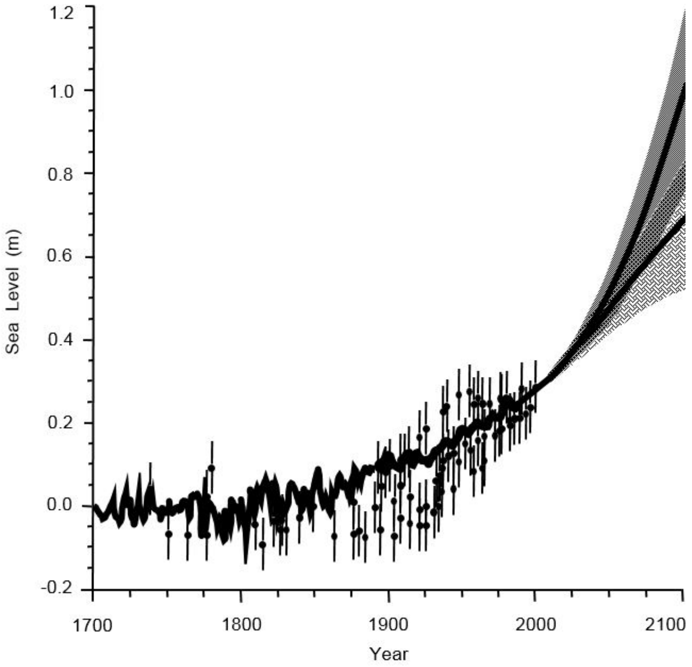

Fig. 2. The global mean sea level rise average rate for the time span between 1700 and 2100 (after IPCC, 2013)

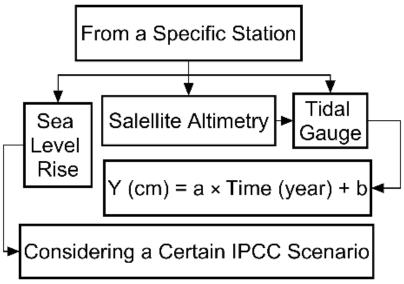

Fig. 3. Sea level rise projection. Note: Y represents sea level rise (cm), a and b are the regression coefficients (dimensionless), and IPCC is the Intergovernmental Panel on Climate Change

Rising sea level impacts attract many researchers' attention, particularly those focusing on the saline water change as a result of this rise in estuaries. Numerous numerical modelling has indicated that rises in sea level have a significant influence on salinity concentrations in estuaries. For example, by estimating a relative rise in sea level of 18 cm to 167 cm by 2100, Hilton et al. (2008) predicted a change of 0.4 to 12 ppt in the Chesapeake Bay salinity, USA. They applied a statistical model to simulate the monthly salinity time series from 1949 to 2006 for 23 grid cells of the bay main stream. Hilton et al. (2008) proved that the residual salinity exhibits an increase over the model run covering 57 years, indicating that there is another influential factor. The Susquehanna River flow increased the bay salinity since 1949. The potentially major future impact of sea level rise on saline water alteration would likely have disastrous impacts on estuarine ecosystems and society. Accordingly, it is essential to note that there is a critical need for further research to be conducted to achieve a better understanding of the relationship between saline water and sea level. Particularly, it is crucial to quantify alterations, both due to sedimentation and dredging, in the bathymetry of a bay, and to quantify those effects on saline intrusion by numerical modelling.

Modelling of surface water salinity intrusion

Brief overview of available models

Table 2 reveals that one of the most widespread codes in current centuries has been the Environment Fluid Dynamics Code (EFDC). The EFDC model is a common purpose modeling package for simulating three-dimensional surface flow, transport and biogeochemical processes including rivers, estuaries, lakes, coastal regions, wetlands, and reservoirs. It was initially established by the Virginia Institute of Marine Science as authorised by US EPA. The EFDC model has three functional modules, such as hydrodynamics, water quality eutrophication, and toxic sediment pollutant movement and fate, entirely integrated into single software. The Mellor and Yamada Level 2.5 Turbulence Closure Scheme (Mellor & Yamada 1982) is implemented in the model (Galperin et al. 1988). The model applies horizontal coordinates, stretched (or sigma) vertical coordinates and curvilinear, orthogonal. It mimics mass and topographically induced circulation in addition to tidal and wind-driven flow rates, and time-based and spatial salinity distributions, temperature, and conservative/non-conservative tracers. The model has a flexible grid and network structure, which is capable of connecting several tributaries to the main channel through grid linkages between downstream and upstream grid cells containing structures of dam.

Jeong et al. (2011) implemented the EFDC model to analysis the upstream movement of salt water features in the downstream stretches of the Geum River basin (South Korea) for four flow conditions (flood, normal, low and drought). They used EFDC to investigate the influence of saline water movement when the gates of the estuary barrage were fully opened. The results suggested that the maximum salt-water concentration can be measured near the barrage of the estuary and the salt-water concentration declined as the distance from the barrage increased.

Table 2. Most widely used salinity intrusion models

Model	Basic model features	Practical salinity intrusion applications
Statistical	-	Gibson and Najjar (2000); Hilton et al. (2008); Zhang et al. (2010); Cai et al. (2012)
Linear programming	-	Sanders and Piasecki (2002)
1D[a]	-	Bhuiyan and Dutta (2012); Fleenor and Bombardelli (2013)
2D[b]	Laterally averaged	Kurup et al. (1998); Hsu et al. (1999);
	Vertically averaged	Liu et al.(2001); Liu et al. (2004); Liu (2005)
	MIKE 21[d]	Kuang et al. (2014)
	MIKE 11[e]	Dat et al. (2011)
3D[c]	EFDC[f]	Jeong et al. (2010); Gong and Shen (2011); Rice et al. (2012); Hong and Shen (2012); Qiu and Zhu (2013)
	SELFE[g]	Chen et al. (2013); Liu and Liu (2014)
	Un-TRIM[h]	Liu et al. (2007)
	FVCOM[i]	Xue et al. (2009)
	MHIOD[j]	Mendes et al. (2013)
	POM[k]	Xiao et al. (2014)
	SUNTANS[l]	
	Chua and Xu (2014)	

[a] One dimensional.
[b] Two dimensional.
[c] Three dimensional.
[d] Two-dimensional Hydrodynamic Model.
[e] Two-dimensional Hydrodynamic Model.
[f] Environment Fluid Dynamics Code.
[g] Eulerian-Lagrangian Finite-Element.
[h] A three-dimensional, time-dependent, baroclinic, hydrodynamic, and salinity numerical model.
[i] Finite Volume Coastal Ocean Model.
[j] A baroclinic finite volume two-dimensional numerical model.
[k] Princeton Ocean Model.
[l] Stanford Unstructured Non-hydrostatic Terrain-following Adaptive Navier–Stokes Simulator.

Gong & Shen (2011) improved a modelling system based on nested grids to simulate the saline water transport processes and the corresponding response of salinity intrusion to alterations in river flow and tidal mixing in the Modaomen Estuary, China. They showed that during neap tides, the estuary gains salt, whilst during spring tides, it loses salt. The researchers also confirmed that the streamflow pulse overturns the corresponding saline water intrusion greatly.

The upstream saline water movement in estuaries results in limited water availability of suitable quality for many purposes, such as domestic and industrial uses. Furthermore, under scenarios with and without the Three Georges Reservoir regulation, Qiu & Zhu (2013) simulated the seasonal saltwater intrusion around the Changjiang Estuary (China) by applying an updated EFDC model. Throughout the dry season, they found that seawater intrusion around the freshwater reservoirs considerably decreased as the Three Georges Reservoir supplemented river discharge. Whereas, during autumn season, this reservoir progressive the timing of salinity intrusion and marginally increased its density. Accordingly, the researchers concluded that the seasonal discharge regulation by the Three Georges Reservoir has both positive and negative impacts on saline water intrusion and freshwater availability during the annual dry and wet periods.

To shed light on the responses of the Chesapeake Bay (USA) to sea level rise scenarios of the 21st century, which are set by the US Climate Change Science Program (Mahoney et al. 2003), Hong & Shen (2012) utilised a three-dimensional hydrodynamic-eutrophication model (HEM-3D). Based on the corresponding numerical results, they pointed out that mean salt content, salinity intrusion and stratification would rise during the dry season greater than in a typical year as the sea level rises. Both salinity concentration and stratification data reveal more likely increases in spring and wet years than in autumn and dry years.

Furthermore, to explain the alteration of transport processes with rising sea levels, the transport time scales were used by Hong & Shen (2012). The corresponding results indicated the following: Firstly, the freshwater downstream transport would be slower while the flow substitution would be reinforced. Secondly, owing to the greater volume and enhanced alteration of circulation, the residence time of the bay would increase. Thirdly, the vertical transport time rises and the volume of water mass for various age groups increases at different rates. Therefore, the retention time of dissolved materials would rise in the bay.

Additionally, by utilising EFDC, Hong & Shen (2012) demonstrated that although the intensified tidal currents would increase due to vertical mixing, the strengthened stratification would weaken the exchange in the vertical level. As a result of stratification changes, the vertical transport time would increase considerably the impact of tidal alterations. The increased upstream transport time has less of an impact on hypoxia environments in the middle and upper bay parts, because the dissolved oxygen provision at the bottom of the bay is dominated by vertical exchanges. Less dissolved oxygen supply from the surface to the bottom region would be recorded due to the weakened vertical exchange. Furthermore, Rice et al. (2012) studied the sea level rise impacts on tidal freshwater wetlands and on the potable water supply of two tributaries of Chesapeake Bay, James River and Chickahominy River using the EFDC model. They used sea level rise scenarios of 30, 50, and 100 cm based on the US Climate Change Science Program (2009; see also above) for the mid-Atlantic region concerning the 21st century (Hong & Shen 2012). For the James River, the results demonstrated that the salt water rises in the lower and upper reaches of the river, and are smaller than those from the middle to the upper river parts. With 50 and 100 cm sea level rises, the maximum saline water increase would be 2 and 4 ppt, respectively, and the upstream movement of the 10 ppt isohaline is much greater than the 5 and 20 ppt isohaline movements. Rice et al. (2012) stated that if the sea level rises by 100 cm, the salinity water volume rises significantly ($p < 0.05$) between 10 and 20 ppt. Whereas in the Chickahominy River, the average salinity at the abstraction point for drinking water, which is located 34 km upstream of the estuary mouth, is likely to be greater than 5 ppt in a dry year and nearly 3 ppt in a typical year. Furthermore, they concluded that for a 1m sea level rise, the James River salinity would move nearly 10 km upstream. Also, Rice et al. (2012) found that during a dry year, the number of days of salinity with more than 0.1 ppt would increase. For instance, 0.1 ppt would be exceeded for ≥ 100 days at a small increase of 30 cm.

The research specifies that EFDC has been effectively applied to a wide range of saline water intrusion model-based investigation issues. Similar with other codes, the key drawbacks that researchers could face when applying EFDC are in computing the trade-off between wanted complication that is required for interpreting the predicted distribution of salinity and long running times, and the model calibration and validation required efforts. Nevertheless, such modelling codes have permitted potentials for simulating three-dimensional surface water and estimating the magnitudes and directions of saline water intrusion under altered future circumstances.

Surface water salinity modelling studies

Many mathematical methods were used to evaluate and mimic the saline water intrusion in the surface water. Previous research mostly concentrated on computing the saline water intrusion as a consequence of sea level rise using two dimensional hydrodynamic models. Examples of such studies include Kuang et al. (2014) who applied a hydrodynamic model (MIKE 21; (DHI 2011)) to investigate the effects of potential future sea level rises in the Yangtze River Estuary. The model simulated sea level rise scenarios of 0.5, 1.0, and 2.0 m during the flood season. According to the

MIKE21 model outcomes and under sea level rise conditions, they concluded the following: (1) the estuarine system tidal level increases and the rate of increase declines slowly upstream along the river; (2) the movements of tidal wave upstream will increase resulting in the upstream progress of a tidal limit and tidal current limit; (3) the flood and ebb velocities will increase; and (4) the North Branch ebb flow has the largest rate of increase, with the ebb flow divided percentage increasing up to nearly 5% under the 2 m sea level rise scenario.

However, Mendes et al. (2013) implemented a baroclinic finite volume two-dimensional numerical model to explore the alterations in current velocity, amplitude and phase of the main semi-diurnal and diurnal tidal constituents associated with the Douro estuary as a result of the potential effect of sea level rise. The study focused on three sea level projections: 0.28 m, 0.42 m and 1.00 m. The first and second scenarios were addressed by Lopes et al. (2011), and the third adopted values used in several studies (e.g., Sano et al. (2011); Yates et al. (2011)). The main finding of these studies is that the amplitude of the principal lunar semi-diurnal tide constituent increased for almost the estuarine area. This arrangement is more obvious in the intertidal region close to the estuary mouth.

Despite the fact that two- and three-dimensional hydrodynamic and solute transport models are better suited to model a complex network of tidally affected flows under future sea level rises, Fleenor & Bombardelli (2013) claimed that a one-dimensional model is computationally more efficient. In order to quickly perform multi-year simulations for this phenomenon, they used a simplified delta network model with a tidally averaged computational approach. They proved that sea level rise will increase saline water throughout the Sacramento-San Joaquin Delta with time. The model is capable of performing very fast simulations over a wide range of conditions, providing guidance on what should be explored in depth with slower models in the future. Bhuiyan & Dutta (2012) used a one-dimensional model to roughly estimate the sea level rise impact in terms of salinity concentration and salt-water intrusion in the coastal area of the Goral river network, South-west Bangladesh, during the dry season. The overall framework of the study has been depicted in Fig. 4. They concluded that a 59 cm rise in sea level increases the salinity by 0.9 ppt at a distance of 80 km upstream of the river mouth. This denotes a sensitivity of 0.9 ppt dividing by 0.59 m equal to 1.5 ppt per meter sea level rise.

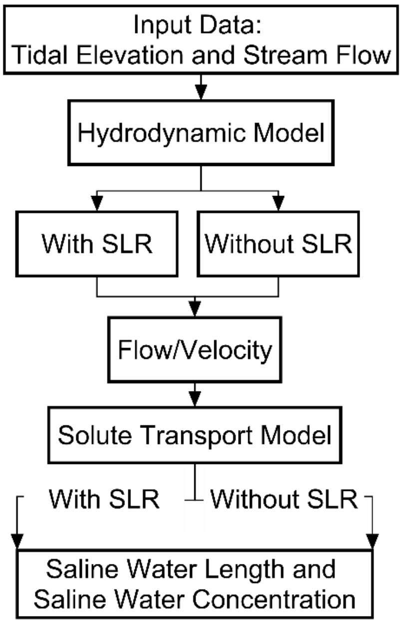

Fig. 4. Saline water intrusion modelling framework as a result of sea level rise (SLR) (after Bhuiyan and Dutta, 2012)

Bhuiyan & Dutta (2012) stated that there is an upstream movement by nearly 21 km for the salinity front at 10 ppt. Moreover, the results reveal that as the flow rate in a particular part is low, the saline water movement is higher in this part. Additionally, Bhuiyan & Dutta (2012) claimed that despite the fact that the salinity transport mechanism is well considered in computation, there is a limitation to the accuracy of this model. Although the lateral river inflow from the floodplain is considered, the salinity from the floodplain is ignored. Accordingly, the floodplain lateral salinity inflow needs to be inserted into the model or considered at a later stage.

Liu & Liu (2014) simulated the distribution of salinity and corresponding transport times with respect to a sea level rise of about 38 cm in 2100 and different flow rate conditions with respect to the Wu River estuary located in central Taiwan, by establishing a three-dimensional hydrodynamic model entitled Eulerian-Lagrangian Finite-Element (SELFE). Their experimental simulations demonstrated that the intensified stratification caused a more substantial gravitation circulation increasing salinity concentration by carrying a higher salinity into the estuary. The researchers claimed that sea level rise increased the water surface elevation despite the fact the it did not change the tide amplitude and it lengthens to the tidal expedition further upstream by 500 and 900 m under the Q_{10} and Q_{90} scenarios, respectively.

Moreover, Liu & Liu (2014) explained that the saline water limits, which were indicated by a 1 psu isohaline, are 3.0 km and 6.5 km for the current and future sea lever rise scenarios, respectively, under the Q_{10} condition, which is the discharge that is equal to or exceeding 10% of the time. Whilst under the Q_{90} condition, such limits were 5.50 km and 8.25 km without and with sea level rise, respectively. The model findings also indicated that the overall flushing time, which offers an assessment of the time over which pollutants are released into the estuary, extracted from the system for high flow without sea level rise is lower in comparison to the sea level rise, but the corresponding flushing time is higher without sea level rise for low flow, if compared to the rise in sea level. The results showed that a sea level rise level indicates not only a variation in salinity intrusion, but also a residence time proliferation, extending the estuary dissolved substance transport, and subsequently leading to a deterioration of the corresponding water quality.

The effects of three sea level rise scenarios (0.34, 1.05, and 1.40 m for the year 2100) impacting on salinity, residence time and the water age of dissolved materials in the Tamsui River estuarine and the nearby coastal sea of northern Taiwan were assessed by Chen et al. (2014). For this partially mixed estuary, a three-dimensional semi-implicit Eulerian-Lagrangian finite-element numerical (SELFE) model has been utilised. The prime finding is that the water age will rise in response to the sea level rise, because the dissolved materials concentration has a longer transport time from the upstream to the downstream locations. This is due to the increase of water volume with sea level rise. The residence time of the total system would also increase by nearly 17% under low flow conditions. In addition, the results revealed that with sea level rise, there will be an increase in the mean salt content and salt intrusion length. The salinity limit advances further toward the reaches in the upstream. The results also indicate that the extreme increment of depth-averaged and tidal-averaged salinity would be 1.1, 2.4, and 3.0 psu, respectively for the sea level rises of 0.34, 1.05, and 1.40 m at the middle of the estuary under the average discharge scenario. Finally, the regression between length of salinity intrusion and upstream freshwater flow are determined corresponding to various sea level rise developments.

The impact of sea level rise on saline water movement in the Saint Mark River estuary has been studied by Xiao et al. (2014). They utilised a three-dimensional hydrodynamic model. They explained that a 0.85-m sea level rise caused a substantial increase in salinity near the Wakulla River with an increase of 9.2 ppt for the surface and 12.7 ppt for bottom salinity. Understanding the potential impacts of sea level rise on saline water intrusion is critical for the environmental and water resources management community to develop climate-adapted management plans and mitigation measures to protect ecosystems.

To study the sea level rise and river flow impacts on estuarine circulation, Chua & Xu (2014) used an idealised estuary model. Firstly, they pointed out that a sea level rise causes a strong longitudinal saline water gradient, indicating an increase in the strength of the gravitational circulation, higher longitudinal dispersion coefficients and increased saline water movement. Secondly, under low-flow conditions, the impacts of sea level rise on salinity intrusion are largest since the sea level rise has a greater effect owing to weaker vertical stratification. Thirdly, a high flow leads to an increase of the gravitational circulation, resulting in large vertical stratification, which causes non-linear feedback between vertical mixing and stratification.

The low-lying Hau River is directly affected by sea level rise owing to global warming. Therefore, to evaluate these impacts on the hydraulic regime and saline water intrusion concerning the Hau River, Doung et al. (2015) developed a two-dimensional hydrodynamic and solute transport model using MIKE-21 (DHI 2011). Yang et al. (2015) combined a watershed model with a hydrodynamic model to predict the impacts of climate change as well as land use and land cover change for both increase in freshwater flow, delivered from snowpack and precipitation, and sea level rise in the Snohomish estuary, north-west Washington State, USA. Huang et al. (2015) studied the potential of future sea level rise on saline water distribution and oyster growth in Apalachicola Bay using wind, tide and flow data for the period between 10 June and 9 July 2005. They examined the sea level rise impacts (0.31 m, 0.50 m, and 1.00 m) coupled with a wide range of flow conditions, such as minimum, average and maximum monthly flow based on the data from 1977 to 2013. Salinity movement under low flow is much higher than that under average flow, while salinity under high flow is much lower than that under mean condition.

Long-term salinity records for the time span between 1950 and 2015 were gathered by the Haskin Shellfish Research Laboratory and the U.S. Geological Survey and, and coupled with non-parametric statistical models by Ross et al. (2015) to assess the climate change impact on salinity distribution in the Delaware estuarine. The model results indicated that while insignificant trends were found at points that are usually upstream of the salt front, various points along the estuary show significantly increasing trends in salinity. In addition, the models indicated a positive correlation between sea level rise and enhancing residual salinity. Additionally, the findings confirmed that wind stress plays a role in driving salinity distributions, consistent with its impact on vertical mixing and Ekman transport (Banas et al. 2004). The latter is part of the Ekman motion theory (Jenkins & Bye 2006). The findings show that future rises in sea level will increase salinity, irrespectively of any alteration in the streamflow.

An increase in knowledge of the potential impact sea level rise on coastal areas and estuaries is important. A sea level rise has a direct effect on salinity intrusion, which in turn can threaten freshwater habitats and drinking water supplies in these areas, which would have disastrous impacts on estuarine ecosystems and society. Furthermore, comprehensive scientific research presenting the amount of climate variation and sea level rise bearing on saline water intrusion compared to other features, such as water abstraction do not exist (Jackson et al. 2013; Mabrouk et al. 2013; Pervez & Henebry 2015). This indicates the need for future research that will assess the sea level rise impact versus extensive abstraction as another factor for salinity intrusion causes.

Avenues for future research

This research concludes with numerous ideas about the potential future directions that could offer valuable inputs for the surface water resources sustainable management from coastal areas. This review is part of an ongoing process to improve understanding of the potential impacts of salinity intrusion in rivers and estuaries, as well as to identify the key scientific questions that need to be addressed in the future. Although there is consensus about the human interventions and sea level rise impacts on salinity intrusion, there is less certainty about the integration between these likely impacts on saline intrusion, especially due to regional changes in sea level rise. However, it is not too early for basin managers and decision-makers to consider long-term adaptation strategies, taking into consideration the following:

They should firstly investigate the positive and negative effects of river regulation on salinity intrusion and freshwater resources during dry and wet periods. Water impoundment in a man-made reservoir is the main cause for reduction in streamflow and strengthened saline water intrusion throughout the wet season. In comparison, water yielded during dry periods dilutes the salinity around the mouth of the river. This is why it is vital to estimate the effects of reservoir regulation and river discharge on the concentration and dispersal of saltwater intrusion in combination with the impacts that might result from a future sea level rise. The dissimilarity between residual water transport before and after river regulation during spring-neap tide will change. Therefore, the focus should be on the spatial and temporal variations of saltwater intrusion, and the impact of seasonal change of river flow on water intakes at the tidally affected reaches.

In the absence of adaptation, saline water intrusion will gradually lead to the decrease in estuarine water quality, so that the corresponding water becomes inappropriate for many uses, such as drinking water, industrial, and agricultural purposes, subsequently causing an increase in poverty, potential population displacement and health issues. However, specific adaptation measures for a geographical region cannot systematically be exported to another coastal environment due to different geophysical, economic, social, cultural, and political regulations. Nevertheless, the general principles for adapting agro-ecosystems to more saline environments, developing crop varieties that are more tolerant to salinity, limiting salinity intrusion or optimising flows and sediment transport upstream through infrastructure development and management, restoring previously degraded coastal ecosystems, and institutional and governance issues, are relevant to most deltas.

Given that the key drivers for more declining effects on estuaries and tidally affected rivers are identified to be sea level rise and increased development-driven surface water abstraction, more investigation with the developed numerical salinity models should be carried out on quantifying variations in surface water and water budget. Scenarios of current climate variation could be applied to formulate potential future sea level and hydrological conditions; while a regional development plans could offer information for future levels and spatial distribution estimation of surface water abstractions.

Exceptional importance should be put on combinations of sea level rise and surface water abstractions and extreme conditions. Likely future variations in the tidally affected rivers at the inflow to the estuary should be inspected as these would be reflected in different boundary conditions of the salinity intrusion models (Mabrouk et al. 2013). The outcomes of the model-based analysis could serve as main objectives for the introduction of probable future moderation and adaptation policies.

The probable effects of moderation and adaptation measures on the basis of the salinity intrusion model-generated results could then be quantified and various measures could subsequently be assessed. Strategies for surface water conditions should be evaluated with and without mitigation scenarios, and the most appropriate scenarios could then be suggested for application.

Thirdly, managers should search for suitable ways to reduce the effects of rising sea level on saline water intrusion. This might include the construction of weirs or a series of weirs to prevent saline intrusion in rivers and estuaries.

Additionally, it would be beneficial to apply computer models to investigate salinity hazards due to an upstream shift of the brackish water zone, resulting from both future rise in sea level and the increase in freshwater diversion from estuarine systems for agricultural, municipal, and industrial uses.

Furthermore, while it is commonly accepted that a sea level rise will change the spatial and temporal distribution of salinity in estuaries, it is not well-known how the estuarine ecology and the abstraction points of drinking water supply will be altered and affected. Further research is recommended on quantifying the association between sea level rise and salinity. Particularly, it will be important to improve the quantification of alterations in the bay bathymetry, due to both sedimentation and subsequent dredging. Moreover, the quantification of those effects on salinity through modelling and subsequent application to other estuaries of the statistical and hydrodynamic modelling techniques (presented in this critical review article) is also advantageous.

It is important to note that there is a critical need for further work to be undertaken to achieve an improved understanding of the link between sea level and saline water. Particularly, the quantification of changes, both due to sedimentation and dredging, in a bay bathymetry, and corresponding effects on saline intrusion by modelling is crucial. There is also a need for a sensitivity analysis to identify the conditions under which the key alterations in the saline water toe are experienced for slight variations in the main hydrogeological variables, and to quantify the location of the toe relative to any recharge dependent water table level.

A decline of fluvial flow in the tidally affected rivers would lead to more intense saline intrusion. Investigations to assess the respond of coastal environments to sea level rise are necessary to better understand water availability for future climate scenarios.

Saline sub-surface water and surface water interactions are a common in the coastal zone of many areas throughout the word, but the hydrological processes and physiographic reasons involved are not totally understood. Further research work is critical to identify such processes and factors that control the spatiotemporal variability and dynamics of this interaction due to climate change and sea level rise, and consequently the involvement of saline sub-surface water to surface water salinity.

Eventually, owing to regional circulation patterns or to vertical land movements, which can be of a similar order (mm/year) of magnitude as sea level rises, the mean of sea level rise can differ dramatically from the universal mean. The unequal alteration of the sea level all over the world is apparent from tidal gauge and satellite altimetry recordings. It follows that it becomes vital to take into account the findings from regional investigations. Although considerable research has been devoted to climate change effects on many estuaries universally, little consideration has been given to these effects on local estuaries.

Conclusions and recommendations

According to this critical review, sea level rise and its impacts on estuaries and tidally affected rivers were the subject of many comprehensive studies going back as early as 1845. Most research studies concentrated on estimating the effect of sea level rise on salinity intrusion regarding surface water. However, more research is needed as the results from these studies are far from conclusive.

Research of sea level rise due to climate change has commonly concentrated on computing effects on coastal areas and surface water. Impacts of sea level rise on groundwater in terms of increased saline water intrusion have been evidently recognised, but quantification of these effects is currently missing. An incorporated groundwater model of the coastal area aquifer that includes freshwater-saltwater interactions could serve as a tool for quantification and characterisation of these effects.

Increased and fundamentally uncontrolled groundwater and surface water abstractions are a possibly serious threat to the salinisation of the coastal aquifers and surface waters. Historical trends demonstrate increases of surface and ground water abstractions since 1845 predominantly modelling studies reported in literature simulate coastal area deterioration as well as salinitation of the tidally affected rivers and aquifers. At the same time, however, the majority of reported modelling studies are of local nature, implemented in specific regions to analyse the problems of a particular zone and interpret the results in terms of impacts caused by abstractions.

Past modelling effort was primarily carried out using two-dimensional vertical or horizontal models. A significant restriction of vertical models is that the representative cross sections should be selected carefully. The horizontal models provide spatial results in horizontal dimensions, but they give less accurate locations and shapes of the transition zone between fresh and saltwater in the vertical dimension.

This condition specifies that future studies should concentrate on the improvement of three-dimensional models, but towing to their intricacy, data requirements and long computational times, such models are hardly developed for seawater intrusion problems. Yet, such models are evidently required: Firstly, they can be used for hypothesis testing and better understanding of the overall system behaviour. Secondly, these models can be used for an integrated assessment of all potential threats salinisation of the area. Finally, once completely advanced, such models can become fundamental works of future preparation platforms and decision systems for assessment of many adaptation and moderation measures.

Acknowledgements

The research presented has been financially supported by the Government of Iraq via a PhD scholarship for the lead author via Babylon University. Special thanks go to Amjad Hussain (The University of Salford) and Maryam Raho (The University of De Limoges) for their kind help and support.

Notation

The following symbols are used in this paper:

EFDC = Environmental Fluid Dynamics Code;

Flushing time = The time needed to replace the estuary freshwater volume at the rate of the net flow;

HEM-3D = Hydrodynamic-Eutrophication Model;

IPCC = Intergovernmental Panel on Climate Change;

Isohaline = A line on a map of the ocean connecting all points of equal salinity;

Hypoxia = Reduced oxygen content of air or a body of water detrimental to aerobic organisms;

MIKE21 = Two-dimensional Hydrodynamic Model;

Neap tide = A tide in which the variation between high and low tide is the least;

ppt = Parts per thousand;

psu = Practical salinity unit;

Q_{10} = The discharge that is equal to or exceeding 10% of time;

Q_{75} = The discharge that is equal to or exceeding 75% of time;

Q_{90} = The discharge that is equal to or exceeding 90% of time;

Q_m = Mean river flow;

SELF = Semi-implicit Euler-Lagrange Finite-element;

Spring tide = A tide that occurs when the difference between high and low is;

Tidal amplitude = The elevation of tidal high water above mean sea level;

Un-TRIM = A three-dimensional, time-dependent, baroclinic, hydrodynamic, and salinity numerical model; and

X_{L0} = The calibrated intrusion length.

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Table 1. References related to salinity intrusion and sea level rise (SLR)

Reference	Location	Finding
Kurup et al. (1998)	Swan River estuary, Australia	The freshwater river inflow is the most critical process impacting on the salt wedge site.
Liu et al. (2004)	Tanshui river system, Taiwan	The average annual salinity was 8.5 parts per thousand (ppt) and 12.8 ppt before and after the construction of the reservoir in this order.
Liu (2005)	Keelung River, Taiwan	The boundaries of saline intrusion before regulation of the channel were further upstream of the river compared to after channel regulation.
Liu et al. (2007)	Danshuei River estuarine, Taiwan	The two-layered circulation within the estuary prevails most often at the estuary mouth.
Xue et al. (2009)	Changjiang River, China	The salt water movement resulted from a complex non-linear interaction process in relation to freshwater flow upstream, tidal currents, water mixing, wind impact and saltwater distribution.
Jeong et al. (2010)	Modaomen Estuary, China	During neap tides, the estuary gains salt, whilst during spring tides, it loses salt.
Cai et al. (2012)	Modaomen Estuary, China	The estuary would be increasingly exposed to salt intrusion and to flooding from storm surges as a result of further deepening, which facilitates the penetration of storm surges into the system.
Bunyan and Dutta (2012)	Goral river network, Bangladesh	A 59-cm rise in sea level increases the salinity by 0.9 ppt at a distance of 80 km upstream of the river mouth.
Rice et al. (2012)	Chesapeake Bay, USA	With 50 cm and 100 cm sea level rises, the maximum salinity increases would be 2 and 4 ppt, respectively.
Chen et al. (2013)	Wu River estuary, Taiwan	More tidal energy will spread into the estuary after weir construction.
Mendes et al. (2013)	Douro estuary, Portugal	The amplitude of the principal lunar semi-diurnal tide constituent increased for almost the entire estuarine area
Liu and Liu (2014)	Wu River estuary, Taiwan	The overall flushing time extracted from the system for high flow without sea level rise is lower in comparison to the sea level rise.
Chen et al. (2014)	Tamsui River estuarine, Taiwan	The maximum increment of depth-averaged and tidal-averaged salinity would be 1.1, 2.4 and 3.0 psu in this order for corresponding sea level rises of 0.34, 1.05 and 1.40 m at the middle region of the estuary under the average discharge scenario.
Kuang et al. (2014)	Yangtze River Estuary	The ebb flow split ratio increases up to almost 5% under a 2-m sea level rise scenario.
Liu and Liu (2014)	Wu River estuary, Taiwan	The tidal expedition further upstream increases by 500 and 900 m under the Q10 and Q90 discharge scenarios, respectively.
Xiao et al. (2014)	Marks River Estuary, USA	A 0.85-m sea level rise caused a substantial increase in salinity near the Wakulla River with an increase of 9.2 ppt for the surface and 12.7 ppt for the bottom salinity.
Chua and Xu (2014)	No specific location (i.e.: idealised estuary model)	A sea level rise causes a strong longitudinal saline water gradient, higher longitudinal dispersion coefficients and increased saline water movement.

Table 2. Most widely used salinity intrusion models

Model	Basic model features	Practical salinity intrusion applications
Statistical	-	Gibson and Najjar (2000); Hilton et al. (2008); Zhang et al. (2010); Cai et al. (2012)
Linear programming	-	Sanders and Piasecki (2002)
1D[a]	-	Bunyan and Dutta (2012); Fleenor and Bombardelli (2013)
2D[b]	Laterally averaged	Kurup et al. (1998); Hsu et al. (1999);
	Vertically averaged	Liu et al.(2001); Liu et al. (2004); Liu (2005)
	MIKE 21[d]	Kuang et al. (2014)
	MIKE 11[e]	Dat et al. (2011)
3D[c]	EFDC[f]	Jeong et al. (2010); Gong and Shen (2011); Rice et al. (2012); Hong and Shen (2012); Qiu and Zhu (2013)
	SELFE[g]	Chen et al. (2013); Liu and Liu (2014)
	Un-TRIM[h]	Liu et al. (2007)
	FVCOM[i]	Xue et al. (2009)
	MHIOD[j]	Mendes et al. (2013)
	POM[k]	Xiao et al. (2014)
	SUNTANS[l]	
	Chua and Xu (2014)	

[a] One dimensional.

[b] Two dimentional.

[c] Three dimentional.

[d] Two-dimensional Hydrodynamic Model.

[e] Two-dimensional Hydrodynamic Model.

[f] Environment Fluid Dynamics Code.

[g] Eulerian-Lagrangian Finite-Element.

[h] A three-dimensional, time-dependent, baroclinic, hydrodynamic and salinity numerical model.

[i] Finite Volume Coastal Ocean Model.

[j] A baroclinic finite volume two-dimensional numerical model.

[k] Princeton Ocean Model.

[l] Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier–Stokes Simulator.

Figure 1

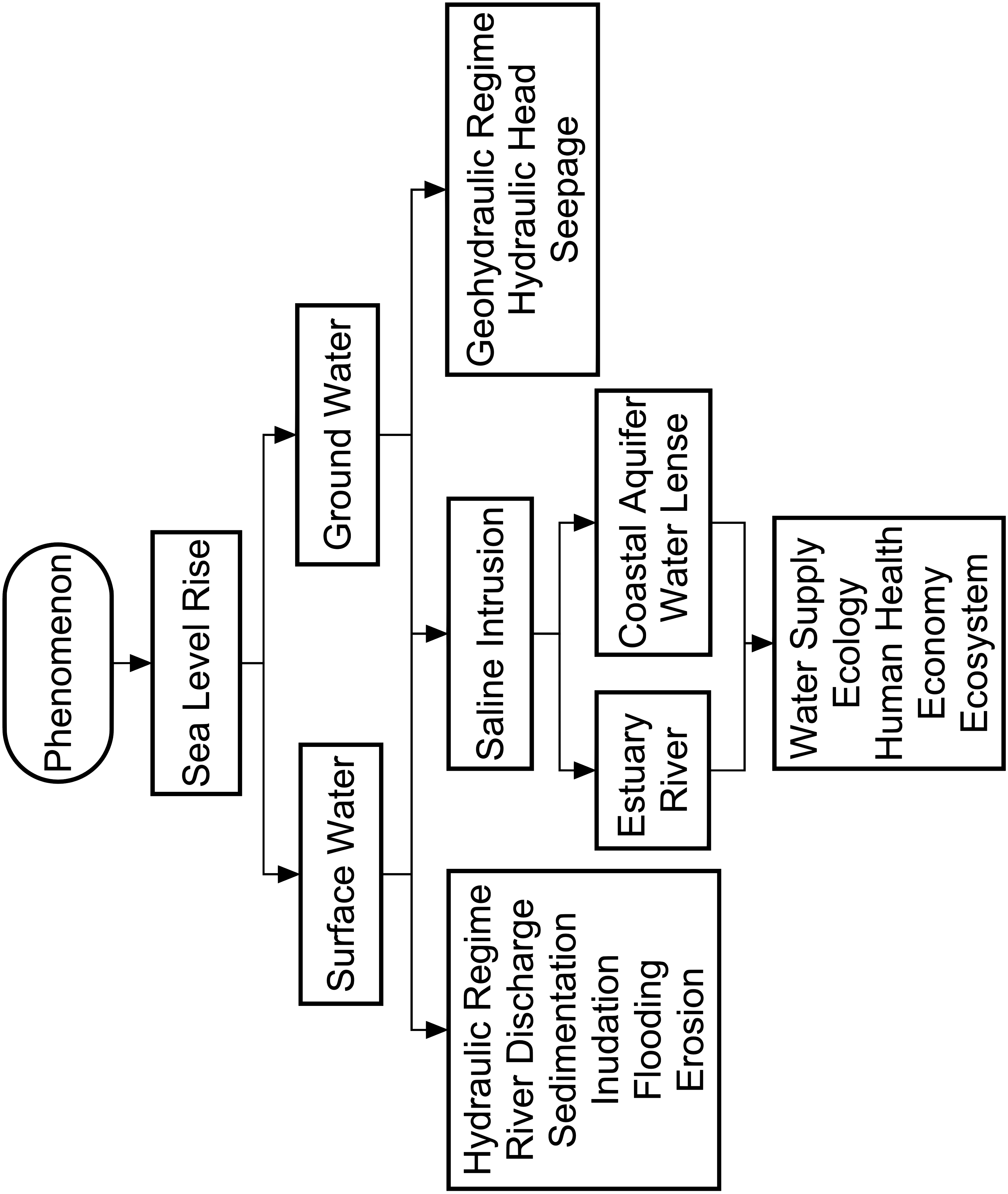

Phenomenon
Sea Level Rise
Ground Water
Surface Water
Geohydraulic Regime
Hydraulic Head
Seepage
Saline Intrusion
Hydraulic Regime
River Dischatge
Sedimentation
Inudation
Flooding
Erosion
Coastal Aquifer
Water Lense
Estuary
River
Water Supply
Ecology
Human Health
Economy
Ecosystem

Figure 2

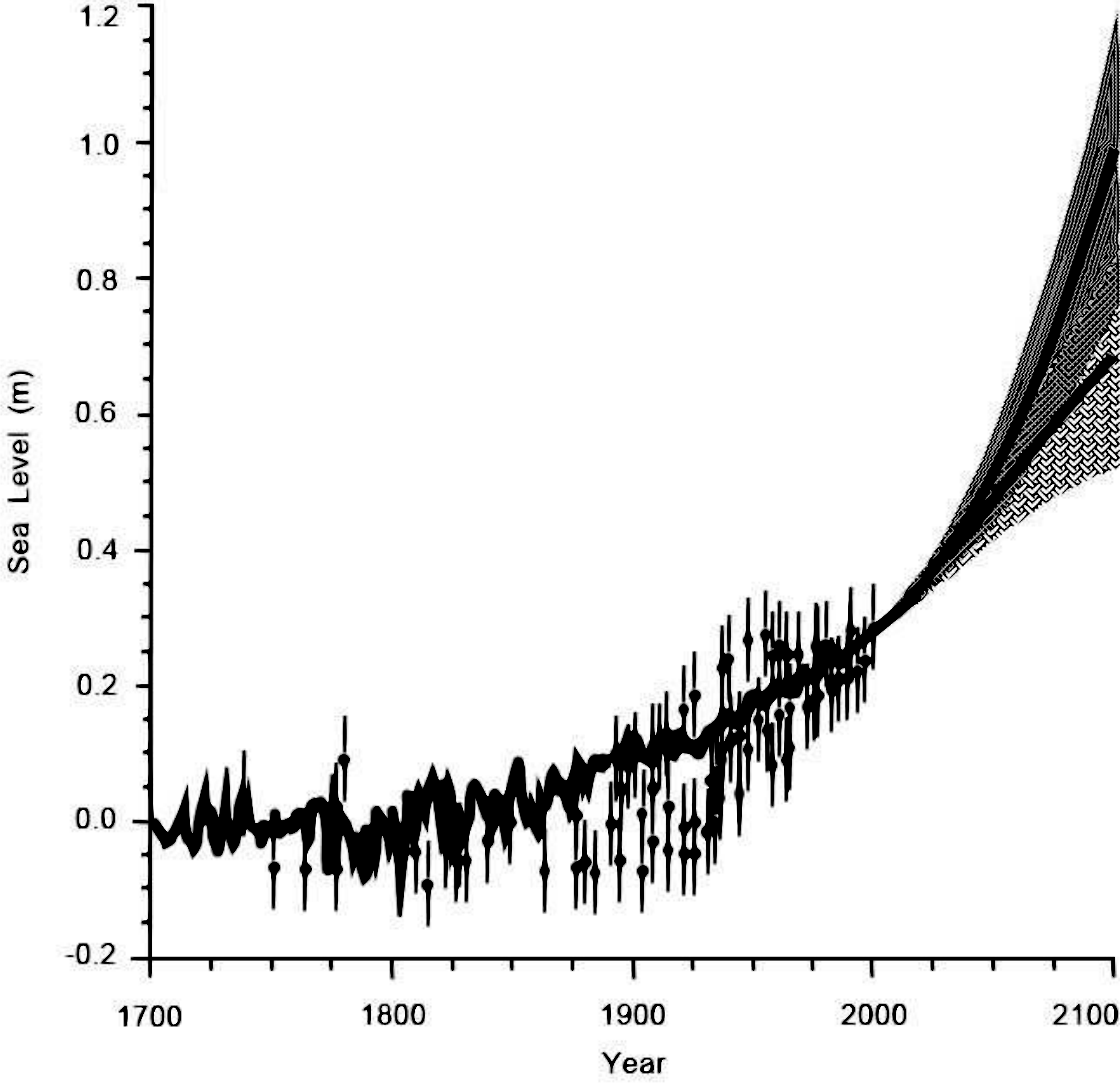


Figure 3

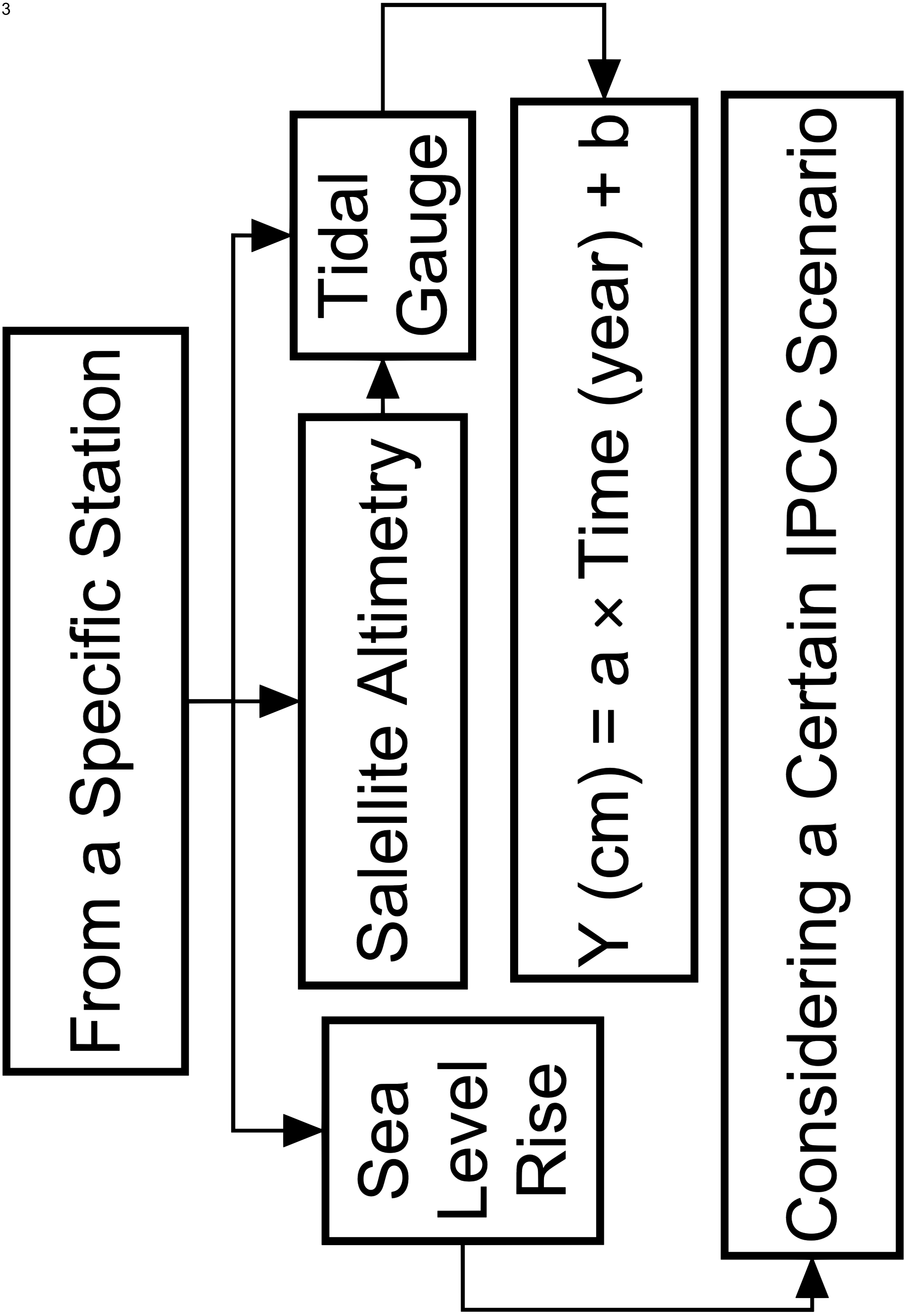
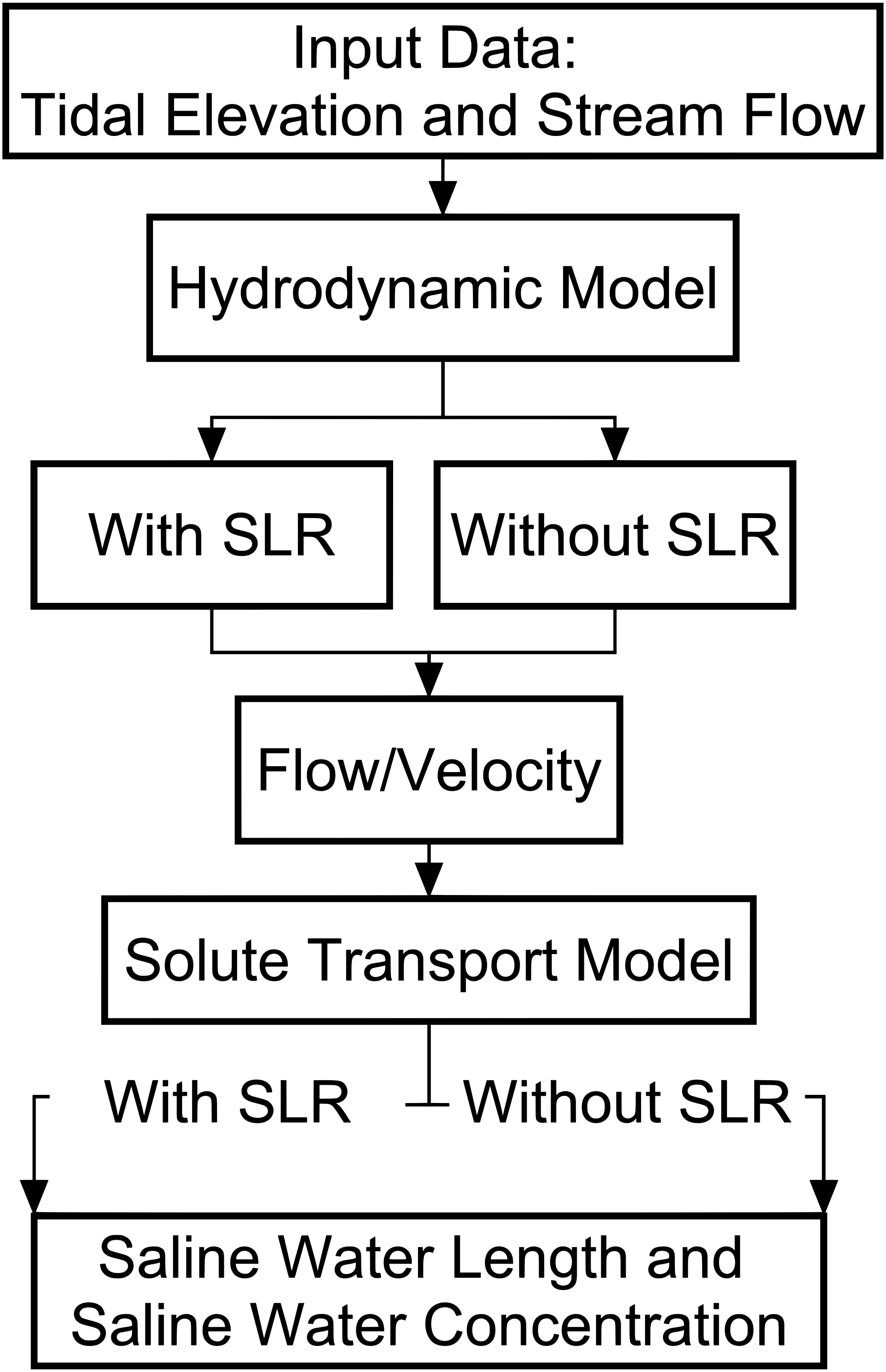

From a Specific Station
Salellite Altimetry
Tidal Gauge
Sea Level Rise
Y (cm) = a × Time (year) + b
Considering a Certain IPCC Scenario

Figure 4


Input Data:
Tidal Elevation and Stream Flow
Hydrodynamic Model
With SLR
Without SLR
Flow/Velocity
Solute Transport Model
With SLR
Without SLR
Saline Water Length and
Saline Water Concentration